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Casting Design

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Introduction

A DESIGN ENGINEER committing pencil to paper is not only creating a shape but also strongly influencing the cost required to place that shape into use. In other words, well-designed parts are less costly to obtain than poorly designed parts and are more likely to be delivered to the customer on time. Although this is true of every method of manufacture, it is particularly true of shapes to be made by the casting process. The casting process has gained the reputation as a technique that can be used to create almost any shape the designer can envision, but whether or not a shape can be cast economically is another matter. If the manufacturing process were considered at the design table, an inherently easier to manufacture design would result. Ease of manufacture translates into castings that are purchased at a lower cost, are of high quality, and are delivered on time.

All aspects of this topic cannot be covered in a single article. However, through an understanding of only a few of the most important aspects of this approach to casting design, a great deal of the potential economic savings can be realized.

Casting Design

Ronald M. Kotschi, Kotschi's Software & Services, Inc.

Solidification

The first aspect that is important to casting designers is an understanding of solidification (the freezing of molten metal inherent in all casting processes). The solidification of a casting can involve as many as three separate contractions as a result of cooling:

- Liquid-liquid contraction
- Liquid-solid contraction
- Solid-solid contraction

Liquid-liquid contraction occurs as a result of the liquid cooling from its pouring temperature (usually 110 to 165 °C, or 200 to 300 °F, above its melting point) down to the melting point or solidification temperature. This particular factor is of little consequence to designers and is fairly easily dealt with by the foundry engineer. However, the design engineer must consider the other two contractions if cost-effective designs and specifications are to be realized.

Solid-solid contraction occurs after a casting has solidified and as it cools from the solidification temperature to room temperature. The design engineer must be concerned with this contraction. To ensure that the dimensions of the casting are correct, the pattern used to produce a given casting usually must be made slightly larger than the casting dimensions at room temperature. The patternmaker compensates for this pattern enlargement for a particular alloy by using a shrink rule specifically for the alloy involved. Further, because the amount of solid contraction is a function of the particular metal to be cast, problems with dimensions can often occur when changing alloys if the same pattern equipment is used. Whenever such a change is contemplated, the foundry engineer should be provided with this information because other factors such as gating and risering could also be involved. Therefore, the designers specifying the alloys should carefully consider any change in alloy to ensure that the cost of new equipment does not cancel out the benefits to be achieved by such changes.

Solid-solid contraction should also be considered in part design, because it is one of the primary causes of warped and cracked castings. A basic concept that governs the way castings cool is the casting modulus (the volume of a portion of a casting divided by the surface area of that portion of the casting). This relationship of geometry to cooling is easily understood by considering the effects of both volume and surface area on cooling rates. As volume increases, more hot metal will be contained within it, and the casting will therefore take longer to cool. Conversely, because all the heat within a casting must pass through a surface at the metal/mold interface, the greater the surface area, the faster the casting will cool. Thus, as the volume-to-surface area ratio (casting modulus) increases, the time required for cooling and solidification is extended.

Using this tool, one can easily see the problems created by the design shown in Fig. 1. Because the design contains a rather wide range of section thicknesses, the various sections will cool and solidify at different rates. The first portion of the casting to solidify would be the sections having a modulus of 1. At some later time, the section with a modulus of 5 would solidify and begin cooling to room temperature. However, the thinner sections will have cooled and contracted by solid-solid contraction before the thicker section, and because of this the thicker section applies a compressive stress to the thinner sections as it cools. Such stresses have been measured to levels as high as 552 MPa (80 ksi), depending on the alloy and section size variations. Therefore, a casting designed in this way will have a strong tendency toward warpage as a result of the imposed stresses. Although a casting may not be warped when taken from the mold, the internal stresses that develop as a result of design can appear at later stages as cracks or warping, often after heat treatment welding, and machining.

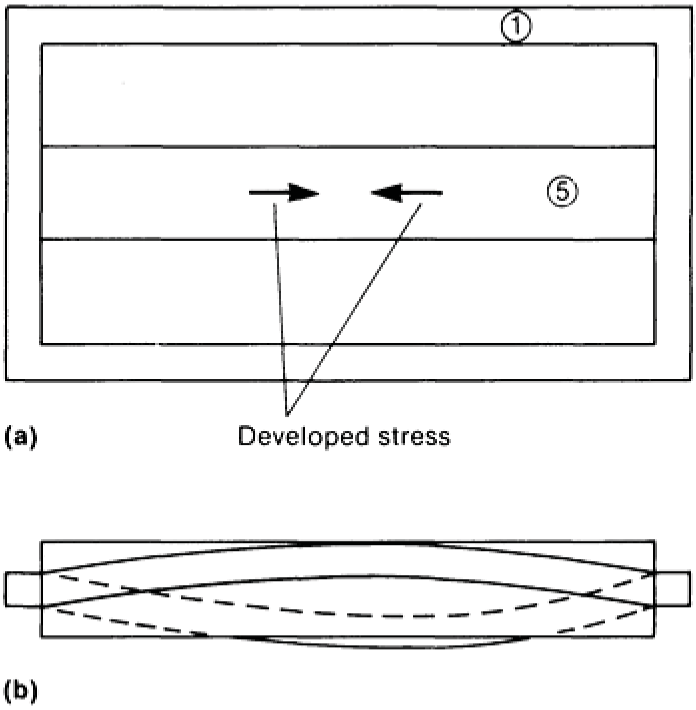

Fig. 1 The effects of design on distortion of castings. (a) Top view of casting; numbers indicate moduli of the two sections. (b) Distortion caused by solidification stresses.

If design features result in warpage, foundrymen often compensate for this by using tie bars that are usually small cast-on bars attached to various parts of the casting to brace the casting and therefore prevent warpage. Although such devices may result in castings that are not warped, other problems can result. For example, such devices cannot prevent the stresses that cause the castings to warp and therefore do nothing to prevent the cause of the problem. In some cases, warpage is eliminated at the expense of increased residual internal stresses. Because such stresses cannot be detected with nondestructive testing, they remain undetected, and upon application of heat or other stresses, warpage, cracking, or premature failure can result. In most cases, castings produced with the bars present no problems in service. However, tie bars do nothing to solve the root cause of the problem, namely, the stresses caused by design features; therefore, it is best to avoid their use by employing uniform section sizes whenever possible.

The importance of solid-solid contraction as applied to design means that an attempt should be made to reduce dramatic variations in the section sizes of castings. Other factors in foundry practice that can lead to the distortion of castings include improper heat-treating practices, difficult-to-collapse molds or cores, shakeout procedures, rigging, and the way in which the casting cools; these factors are under the control of the foundry engineer. Problems with warpage and cracks can often be eliminated through the cooperative effort of casting designers and foundry engineers.

Liquid-solid contraction is by far the greatest difficulty due to solidification that faces the foundry engineer. It is also one of the greatest opportunities for the design engineer to design for low cost, high quality, and timely delivery. Most metals contract as they pass from the liquid to the solid state. Certain compositions of gray and ductile iron are the exceptions to this rule in the major alloys produced by foundries. The entire founding process is possible only because volumetric contraction locates itself in solidifying castings in a systematic way.

Solidification Sequence

The aspect of liquid-solid contraction that allows castings to be produced is that all of the contraction is concentrated in the last portion(s) of the casting to solidify. The foundryman uses this principle to produce sound castings by attaching a volume of metal to the last portion of the casting to solidify. This technique is illustrated in Fig. 2. Such feed metal reservoirs are called risers. Proper placement of risers on castings changes the way in which both casting and riser(s) solidify such that the riser is the last to solidify. When used properly, this produces a casting free of shrinkage because all the shrinkage for the entire mass of both casting and riser will be concentrated in the riser. However, in many cases, the design of the casting restricts the proper placement of risers, making the production of sound castings difficult if not impossible. In this way, casting designers have a significant impact on quality and cost.

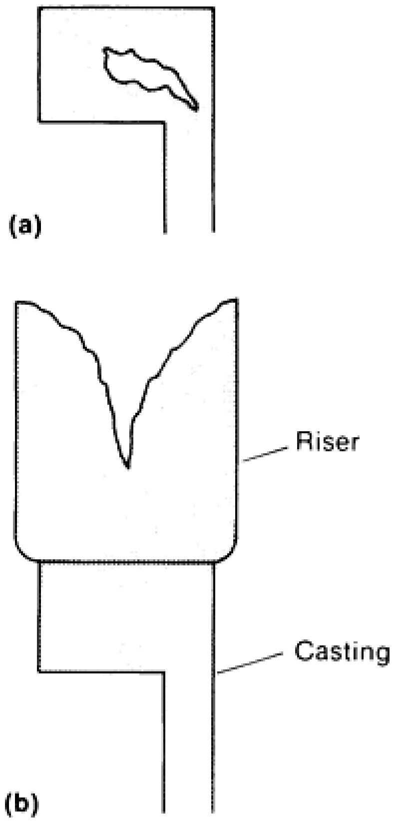

Fig. 2 The function of risers. (a) Shrinkage in casting at last portion to solidify without a riser. (b) Shrinkage in riser allows the production of a sound casting.

The technique of designing castings that are easily risered can be best understood by considering a simple shape such as a wedge (Fig. 3a). The solidification direction, as seen in Fig. 3(b), is related to the casting modulus, which is the volume-to-surface-area ratio. Because a wedge casting has a natural solidification direction, if the design is such that a riser cannot be placed at the wide end of the wedge, a shrinkage cavity will develop in the casting even though a riser was attached. As shown in Fig. 3(a), this occurs because solidification begins somewhere near the middle of the wedge/riser combination. Thus, from a solidification or thermal design point of view, there are actually two castings in this example, each having a last place to solidify. If the design allows for the placement of the riser at the proper end of the wedge, as in Fig. 3(b), a sound casting will result because of the unidirectional solidification pattern. Shrinkage defects may not always represent a problem, but in cases where they jeopardize mechanical strength, appearance, or pressure tightness, the castings would have to be repaired or scrapped. Under such circumstances, the final costs (including delays in delivery) can be severe.

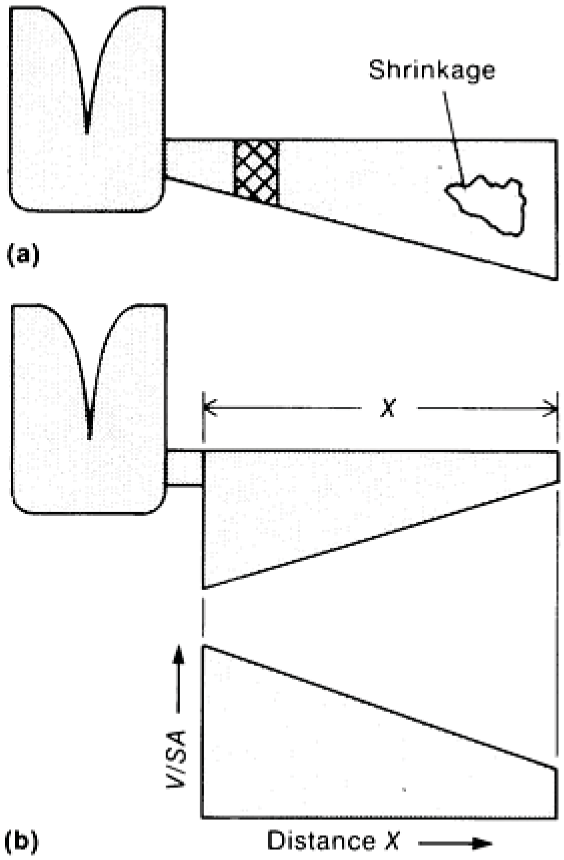

Fig. 3 Casting design and solidification of a simple wedge. (a) Riser placed at narrow end of wedge; shrinkage occurs at wide end. The crosshatched region represents the approximate area of the casting where solidification is first complete, thus cutting off the feeding path of the casting. (b) Correct riser placement. *V*/*SA* is the volume-to-surface-area ratio (casting modulus).

Very few castings are as simple as the wedge shown in Fig. 3; therefore, a technique capable of determining the solidification sequence of complex shapes is needed if design engineers are to take advantage of the potential cost savings. Regardless of their apparent complexity, castings can usually be resolved into a series of rather simple shapes that make up the complex shape. These simple shapes are:

- T-sections (plate intersections forming a T)
- X-sections (plate intersections forming an X)
- L-sections (plate intersections forming an L)
- Plates
- Cylinders
- Cylinder/plate intersections

Most casting geometries can be covered by using these basic shapes. For example, a box shape can be simulated by a series of L-sections, and a hub casting can be simulated as a T-section revolved about a central axis. By solving the relationship between casting design parameters and the manner in which these simple shapes solidify, designers can obtain a useful guide to cost reduction and improved quality through casting design.

T-Sections

Figure 4(a) shows a hub casting. There are four possible ways to position the risers, depending on the casting design. These four alternatives are shown in Fig. 4(b) and 4(c). Selection of one of these alternatives by the foundry engineer depends on the casting design. Figure 4(d) shows the dimensions and critical sections involved. In Fig. 4(d), as well as in each figure in this article that illustrates the dimensions of a given section type, a special notation is used to differentiate between the dimensions describing the size of the section components and the section itself. Although the same letter is used, for example, T and *T*, the roman T refers to the section, while the italic *T* refers to the dimension of the section.

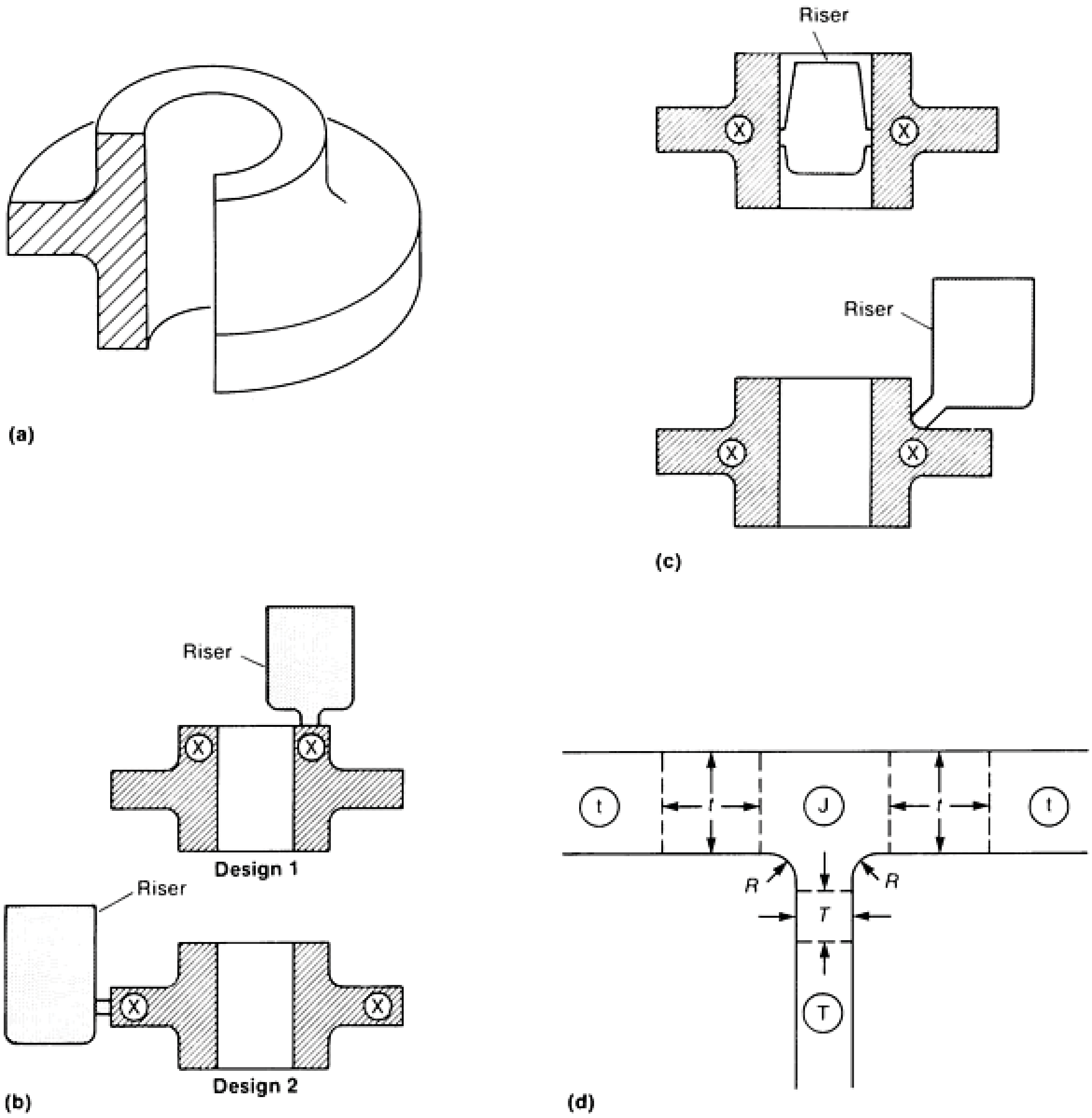

Fig. 4 Cross section (a) of a hub casting showing that it is actually a T-section revolved around an axis. (b) and (c) Possible riser placements; X indicates the last portion of the casting to solidify. See text for discussion. (d) Principal design dimensions of T-section and component sections; see text for discussion.

Factors Influencing the Solidification Sequence. There are three basic design dimensions for a T-section: *t*, *T*, and *R*. If the cross plate dimension *t* is large with respect to the intersection plate dimension *T*, the last portion of the casting to solidify will be area t in Fig. 4(d). This will require the riser placement labeled Design 1 in Fig. 4(b). If the intersecting plate dimension *T* is large compared to that of the cross plate dimension *t*, the last portion to solidify will be area T in Fig. 4(d). This type of design will require the riser placement labeled Design 2 in Fig. 4(b). Finally, if the dimensions *t* and *T* are nearly the same, either of the two possibilities shown in Fig. 4(c) can be used, because area J in Fig. 4(d) will tend to be the last area of the casting to solidify.

In a solidification sequence in which the last portion of a hub casting to solidify is the J portion of the T-section, as shown in Fig. 4(d), one of two difficulties usually arises. In many designs of this type, the hole cavity formed by the rotation of the T-section about its central axis is too small to allow a riser of sufficient size to feed the section. When this cavity is too small, there is no alternative but to place the riser outside of the casting, as shown in Fig. 4(c), which necessitates the use of a core, thus adding cost.

If the enclosed cavity should be large enough to contain a riser of sufficient size, the problem then usually involves the removal of the riser from within the cavity. In a high-production environment, such as automotive applications, special equipment to extract such internal risers can be economically feasible if the design allows placement in the internal cavity of the hub.

Such a special case is the manner in which cast automotive connecting rods are produced. For this particular type of casting, a small wafer riser is placed within the crankshaft receiver end of the connecting rod, which adequately feeds this portion of the casting. However, the use of this casting design and the wafer riser is predicated on high production requirements, which allow the use of specially designed punch presses to remove the riser and the associated gating system. Without such special equipment, the internal riser placement would be highly undesirable.

This case is an exception to the overall undesirable nature of solidification sequences in which the J portion of a hub casting is the last section to solidify. This points out a very important concept; There are no definitive rules that always apply to casting design. It is this potential for alternative solutions based on specialized conditions that makes the topic of casting design so interesting but very difficult to confine within a rigid set of guidelines. The goal is to design the casting with a particular solidification sequence in mind so that the cast part can be risered easily and subsequent riser removal can be accomplished with ease.

In general, however, either of the two riser placements shown in Fig. 4(c) can usually be considered undesirable. Because of the added costs imposed by a solidification sequence of this type, such designs generally should be avoided. However, if such a design is unavoidable, some modifications can be made to facilitate manufacture. The key is to recognize the problem, namely, that area J of the T-section of the hub (Fig. 4d) is the last to solidify. Once this is known, appropriate measures can be taken to modify the solidification sequence.

One alternative would be to alter the casting modulus by changing the shape of the hub to reduce the volume contained and/or to increase the surface area. This would be an effective solution to the problem if the design already required a core to form the hole in the hub before the change in shape. If such a design change increases the number of cores required to produce the casting, this technique may not be cost effective, because additional cores usually necessitate increased casting costs.

Another possible solution to the same solidification sequence problem might be the use of a feed pad (Fig. 5). Once again, by recognizing the solidification sequence problem imposed by the design, the designer could elect to add metal to the flange of the hub to change the solidification sequence. Foundrymen refer to this technique as padding. This is a good alternative solution if the pad can either remain on the casting in use or does not affect machining costs adversely. There are many other possible design alternatives, but the designer must first be aware of the problem caused by the solidification sequence.

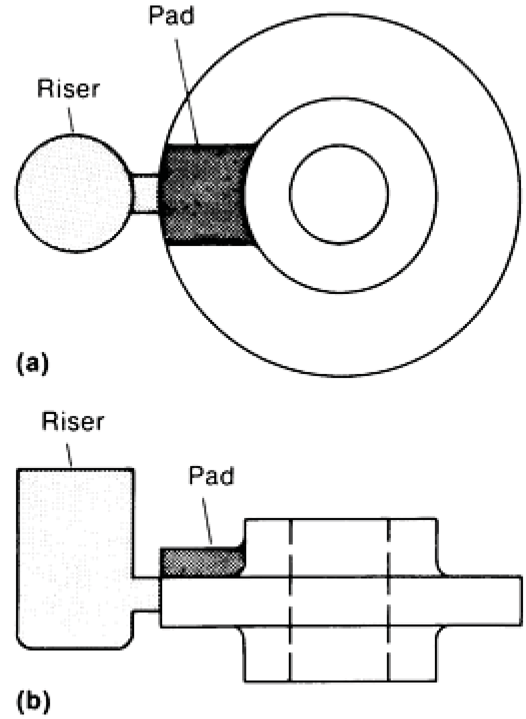

Fig. 5 A hub casting with a pad to provide a feeding channel from the riser. (a) Top view. (b) Side view.

Either of the riser placements shown in Fig. 4(b) is an effective alternative if large production quantities are not required. Because of the need to extract the riser through the top of the cope half of the mold, Design 1 is less compatible with high-production molding techniques than the side riser used in Design 2. Therefore, if high production is expected, the preferred solidification sequence would be that in which area T in Fig. 4(d) is the last portion of the casting to solidify.

Development of Solidification Sequence Graphs. A series of graphs has been developed to assist designers and foundry engineers in determining the solidification sequence of the basic shapes listed earlier. These graphs show the solidification sequences as a function of the design parameters constituting the sections. Considering the T-section shown in Fig. 4(d), one can easily see that there are three parameters governing the manner in which the section solidifies, namely, dimensions *T*, *t*, and *R*. As each of these parameters changes, the casting modulus of each component making up the T-section changes. The solidification sequence can be estimated by comparing the modulus of each component (t, T, and J) of the T-section. With the use of a computer, this process was employed to evaluate all the possible designs of the T-section from *t* = 0 to 10 and *T* = 0 to 10 while holding *R* = 0. The results of this analysis are shown in Fig. 6(a).

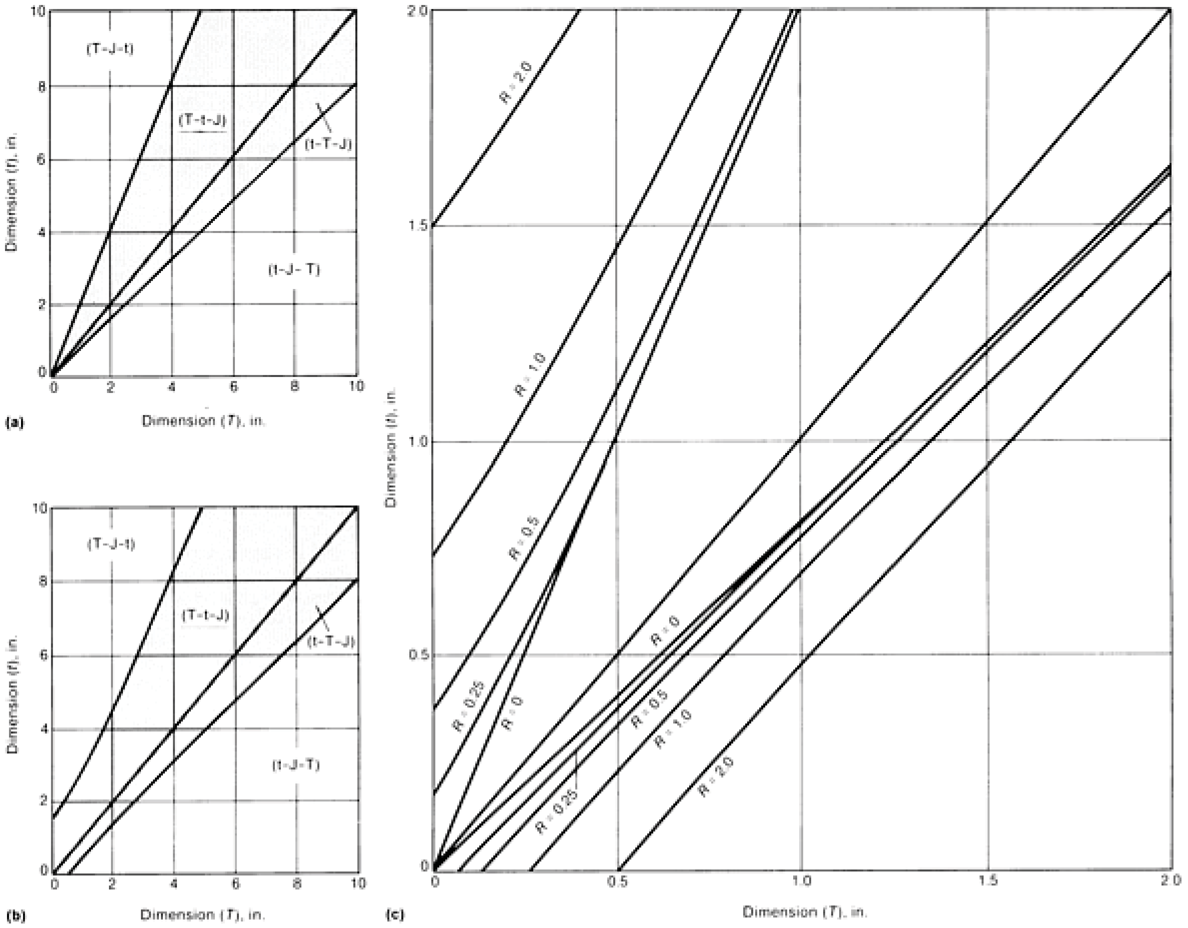

Fig. 6 Solidification sequence curves for T-sections. Letters indicate the order of solidification of the various parts of the casting (see Fig. 4d). (a) Fillet radius R = 0. (b) R = 2. (c) Composite of design curves for various fillet radii.

The technique used in this analysis was the well-known Chvorinov's rule, which is commonly used to compare the solidification times of simple casting shapes. Although originally developed for the solidification of pure metals and alloys solidifying over a very narrow temperature interval, the concept is more broadly applicable and states that the total solidification time of a casting (or casting section) is proportional to the square of the volume-to-area ratio of the casting (or casting section). This rule can be stated mathematically as follows:

$$t_f = K.\left(\frac{Vc}{Ac}\right)^2$$

where t_f is the total solidification time for the casting or casting section, V_c is the volume of the casting or casting section, A_c is the surface area of the casting or casting section, and K is a constant for a given metal and mold combination.

The factors that relate to the constant K are mold temperature, metal temperature, the density of the solidifying metal, the specific heat of the mold, the density of the mold material(s), the thermal conductivity of the metal, the thermal conductivity of the mold, and the specific heat of the metal. These factors involve the specifics of a given casting manufactured in a given mold. For a mold that consists of a single material, these factors can be considered a constant throughout the mold.

For factors that are constant throughout the part of the mold containing a given portion of the casting, Chvorinov's rule becomes a proportional equation in which the time for solidification is proportional to the square of the volume divided by the surface area. In this form, the results of the equation are independent of the type of mold and metal being considered, provided they are the same over the casting section to which the results are to be applied. Furthermore, for the purposes of providing a proper solidification sequence, the actual time for a given portion of a casting to solidify is not needed. In this type of analysis, it is important only to determine the order in which each component solidifies with respect to the other components being studied. By remembering these facts, the proportionality equation discussed above (that is, solidification time is proportional to the volume/surface area ratio) is all that is required to study the solidification sequence of various section components relative to one another.

Consider the components making up the T-section in Fig. 4(d). There are three basic dimensions (T, t, and R) that describe the section, and the section consists of two plates labeled T and t whose intersection forms another section labeled J. Assuming from a thermal point of view that the formed section is infinite (that is, the ends of plates in the z-direction perpendicular to the drawn section do not influence the solidification of the section or the plates), the volume of the section and plates can be determined from the perimeter and enclosed cross-sectional areas of the sections. Such an assumption is valid if the thickness of the section in the z-direction is five times the thickness of the thickest section.

For this case, the volume of the plate having a thickness T is equal to T^2. The surface area is equal to $2T$; therefore, the volume-to-surface-area ratio (casting modulus) of the plate is $T/2$. Similarly, it can be shown that the casting modulus for the other plate making up the section is $t/2$. To study the relationship of the solidification sequence of all the components making up the T-junction, all that remains is to develop the casting modulus for the junction of the two plates referred to as J in Fig. 4(d). Assuming that the thermal effect of the junction extends one plate thickness beyond the tangent point of the radii (that is, the junction length along the t plate is considered to be $2t + 2R + T$), the volume and surface area of the junction can be written as follows:

$$Volume = 2r^2 + t(2R+T) + RT + T^2 + \frac{(4R^2 - 3.1416R^2)}{2} \qquad \textbf{(Eq 1)}$$

$$\text{Surface area} = 4t + 2R + T + 3.1416\,R + 2T \qquad \textbf{(Eq 2)}$$

Therefore, the casting moduli for the T-junction J and the plates making up the junction are as follows. For the t-plate, the casting modulus is $t/2$. For the T-plate, the casting modulus is $T/2$. For the J section (the T-junction itself), the casting modulus is:

$$\frac{2r^2 + 2Rt + tT + RT + T^2 + 0.4292R^2}{4t + 3T + 5.1416R} \qquad \textbf{(Eq 3)}$$

Based on Eq 1, 2, and 3 and the design parameters of R, t, and T, it is a simple matter to determine the solidification sequence of a T-section. By entering the dimensions of t, T, and R into the respective equations and calculating the resulting casting moduli, one obtains the solidification sequences based on the design parameters of the T-section and the plates making up the section. The results of such calculations for values of $R = 0$ and $R = 2.0$ for plate thicknesses from 0 to 10 are shown in Fig. 6(a) and 6(b).

A series of T-section design curves for R values of 0, 0.25, 0.5, 1.0, and 2.0 for values of t and T from 0 to 2 are presented in Fig. 6(c). For design curves not covered, one can easily use Eq 1, 2, and 3 for the junction and the respective plates of thickness t and T.

Equations 1, 2, and 3 are not specific for the use of inches only, because the form of Eq 1, 2, and 3 and the results are purely numeric. Thus, one can use metric units such as centimeters or millimeters as the dimensions and use any of the graphs directly. Equations 1, 2, and 3 also allow the user to convert any of the graphs to any radius. All that is needed is to determine a ratio of the desired radius to a specific radius on the graph and then use this ratio as a scaling factor to adjust the scale of the two dimensional axes t and T. For example, assume a graph for a 1 in. or 1 cm radius was needed but only Fig. 6(b) was available. Because the scaling ratio for this case is $\frac{1}{2}$, the T dimension of the horizontal axis could be labeled 0, 1, 2, 3, 4, and 5, replacing the 0, 2, 4, 6, 8, and 10 currently on the graph. By following this same procedure for the t dimension on the vertical scale, one would produce the graph form necessary for the $R = 1$ problem. Thus, the user of these graphs is not limited to the cases presented, and any combination based on the required R value can be used.

The following example further illustrates the use of such curves. Figure 4(a) shows the cross section of a hub casting. With reference to Fig. 4(d), it can be determined that the T-section dimensions are as follows:

- $T = 4$ in.
- $t = 6$ in.
- $R = 0$

Note that T-sections with $R = 0$ are not recommended, because of the stress concentration and the potential for hot tears or cracks.

By referring to Fig. 6(a) and plotting the T and t dimensions, it can be seen that for this design the $T = 4$, $t = 6$ point on the graph lies in the zone of the graph labeled T-t-J. Thus, based on casting modulus, a solidification sequence of T-t-J would be expected. Because the J portion of the section is the last to solidify, the riser would have to be attached to this portion of the casting. Therefore, because of the solidification sequence imposed, a riser placement scheme similar to that shown in Fig. 4(c) must be used. However, this type of solidification sequence is generally undesirable, and design alternatives should be considered. Some metal can be removed from the junction, or the T dimension should be increased somewhat above 8 in. as either a pad (Fig. 5) or a complete increase of the entire flange of the casting. Yet another approach would be to increase or decrease the hub thickness dimension t.

These are a few of the potential solutions to the problem that are available to the design engineer. The designer knows both the stresses and the environment in which the part will function; therefore, the designer alone must make the final decision on any proposed changes. It is important to inform the design engineer of a potential manufacturing problem early in the designing process while flexibility still exists, not at later stages when the flexibility is lost.

The previous example considered a T-section in which the radius R was 0. This case is somewhat academic because, in terms of well-known design principles, the design discussed leads to undue stress concentrations at the sharp corners. This is to be avoided from the standpoints of pure design and casting manufacture. Because of the contraction of the metal as it solidifies and cools, such stress concentration can lead to cracking of the casting (either hot tearing or cold cracking). *Therefore, the first rule of economical casting design is to use generous fillet radii whenever possible*.

Figure 6(b) was obtained by following the same procedure discussed for the development of Fig. 6(a). In Fig. 6(b), the radius dimension R of Fig. 4(a) was set to 2 in. A comparison of Fig. 6(a) and 6(b) reveals the effects of adding a 2 in. fillet radius. Very little difference in the solidification sequence is observed at the heavy plate thicknesses (the upper right-hand corner of the graph). However, in those designs in which thin plates are used (the lower left-hand corner of the graph), there is a much stronger tendency for the plate junction J to be the last portion of the T-section to solidify. It must be remembered that Fig. 6(b) represents all the design variations of the T-section from T and $t = 0$ to T and $t = 10$ to which a constant 2 in. fillet radius is applied. A series of design curves for various fillet radii are shown in Fig. 6(c).

Whenever any fillet radius is applied, an effect on the solidification sequence must be expected because the fillet radius causes an increase in volume and a decrease in surface area in the vicinity of the fillet. The increase in volume and the decrease in surface area caused by the use of a fillet are only functions of the fillet radius; therefore, the effect of adding a given fillet radius to the casting modulus of the t-junction is a constant based on the radius. Furthermore, because the casting modulus of the junction is a function of the plate thickness, the addition of a 2 in. fillet to thin plate designs increases the casting modulus of the junction far more with respect to the modulus of the plate than for thick plates. Thus, the effect of the 2 in. fillet addition is far greater in thin plate designs than in heavier plate T-sections.

Using these graphs, the designer can recognize potential problem areas by remembering *the second rule of casting design for economy, which states that the last place of any casting to solidify must be accessible for riser placement*. Ideal riser placement is at the parting line and at the outer perimeter of the casting. If this rule is not followed, weld repair, scrapped castings or sudden catastrophic failure could result, and these outcomes will cause increased casting costs, delivery delays, and a serious danger of premature failure.

X-Sections

Another simple shape of importance to designers is the X-section. However, for X-sections, the designer must consider two conditions in order to cover all the possible design combinations that might be encountered.

Equal Opposite Legs. The first type of X-section design is that in which the opposite legs of the X are equal. The model for this case is shown in Fig. 7. The solidification sequence curves of this model, which contain fillet radii of $R = 0$ and $R = 2$, are presented in Fig. 8(a) and 8(b). Design curves for various fillet radii are shown in Fig. 8(c). As before, the casting modulus equations for the plates making up the X-section are $T/2$ and $t/2$. For X-sections in which the opposite legs of the section are equal, the casting modulus for the J- or X-junction is as follows:

$$\frac{Volume}{Surface\ \text{Area}} = \frac{2t^2 + 2T^2 + 2Rt + 0.8584R^2}{4t + 4T + 6.2832R} \qquad \textbf{(Eq 4)}$$

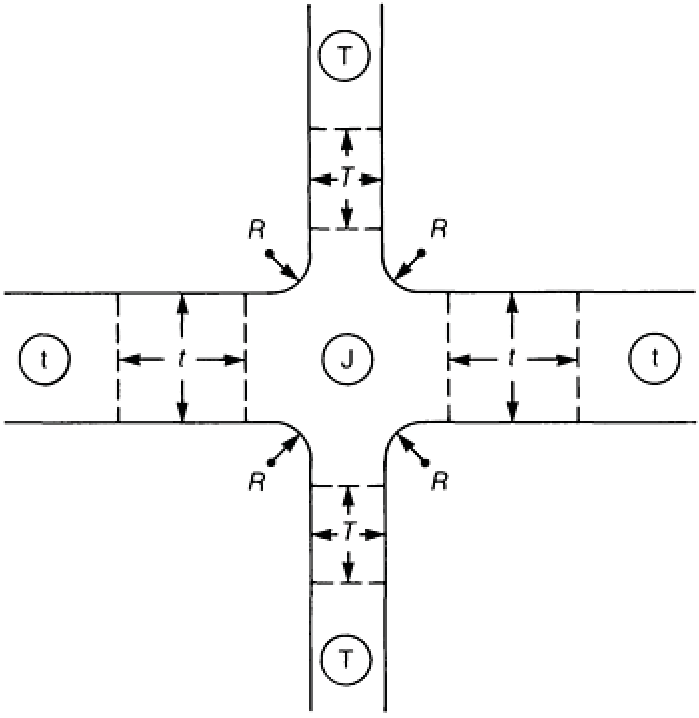

Fig. 7 Model of X-section with opposite legs equal. See Fig. 8 for solidification sequence curves.

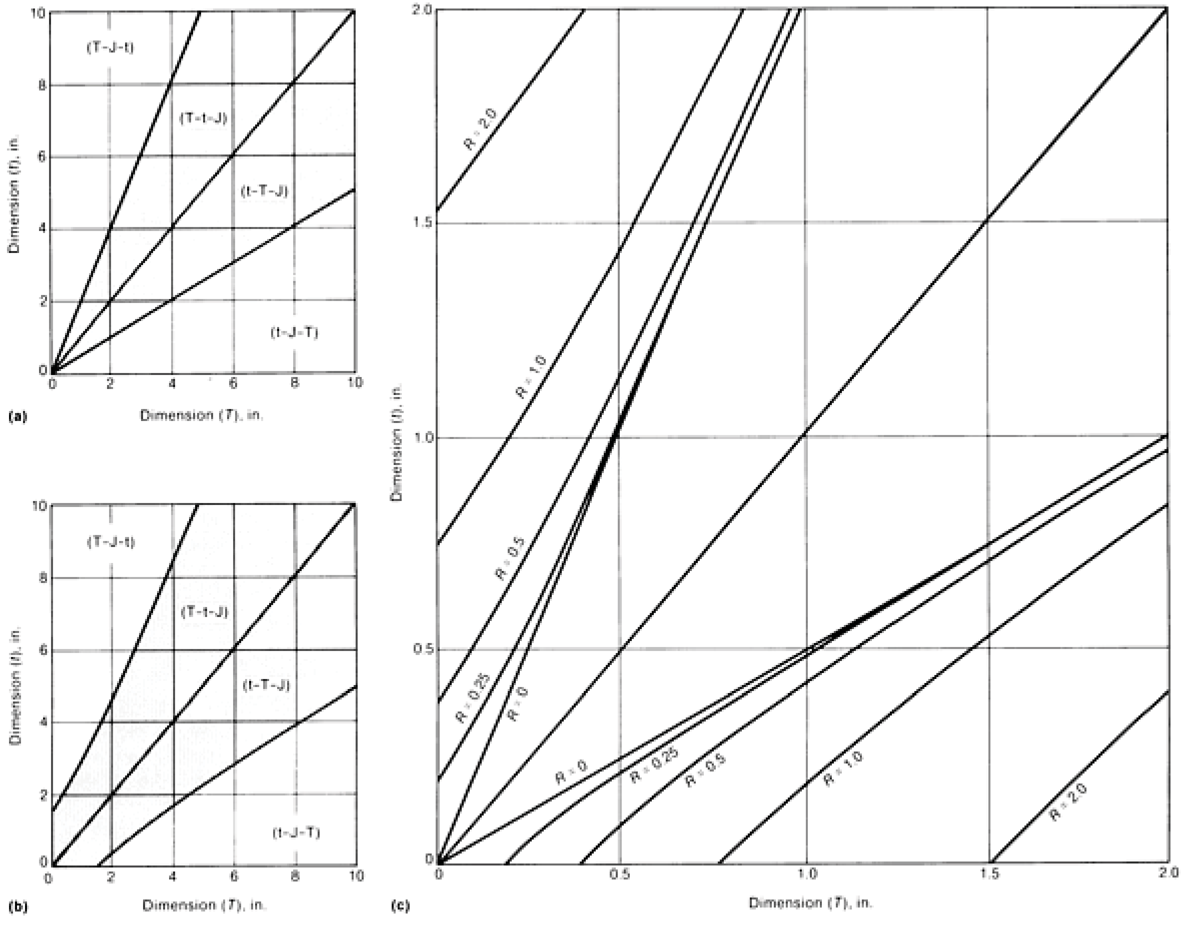

Fig. 8 Solidification sequence curves for X-section with opposite legs equal (see Fig. 7). (a) *R* = 0. (b) *R* = 2.

(c) Composite of design curves for various fillet radii.

Because of the greater volume of metal at the junction, there are far more designs in which the J- or X-junction is the last to solidify compared to the T-junction curves discussed earlier. This is why many authors do not recommend the use of X-sections in casting design. However, this type of thinking can often cause excellent opportunities for cost reduction to be overlooked.

Merely because the junction portion of an X, T, L, or boss section solidifies last does not mean that the section is poorly designed. The most economically produced design will often take advantage of this very fact. The junction of a section solidifying last becomes a problem only when it violates the second rule of economical casting design; that is, it leaves that portion of the casting solidifying last in an inaccessible area for riser placement. Although accessibility for riser placement is essential, limiting the number of risers required can further improve economy by design. *Thus, the third rule for economical design is to create designs requiring as few risers as possible.*

Solidification proceeds through the casting in what is called the solidification or feeding path. Each feeding path will require a riser, and each riser adds to the cost of the casting. Less expensive and better-quality castings will result from reducing the number of feeding paths and ensuring that the end of each feeding path is accessible. Therefore, designs in which the junctions solidify last can be advantageously used to combine feeding paths, thus reducing the overall cost while increasing the quality of the part.

Three Legs Equal. The second type of X-section is shown in Fig. 9. In this design, three of the plates constituting the section have the same thickness. The corresponding solidification sequence curves for this case in which $R = 0$ and $R = 2$ are shown in Fig. 10(a) and 10(b), respectively. There is a difference in the curves across the isothickness line running diagonally from left to right on the curves. The upper left portions of the curves represent those designs in which a thick plate of dimension t is being chilled by the three equal thickness plates whose dimensions are T. This portion of the curve is similar to the curves discussed previously and is fairly straightforward.

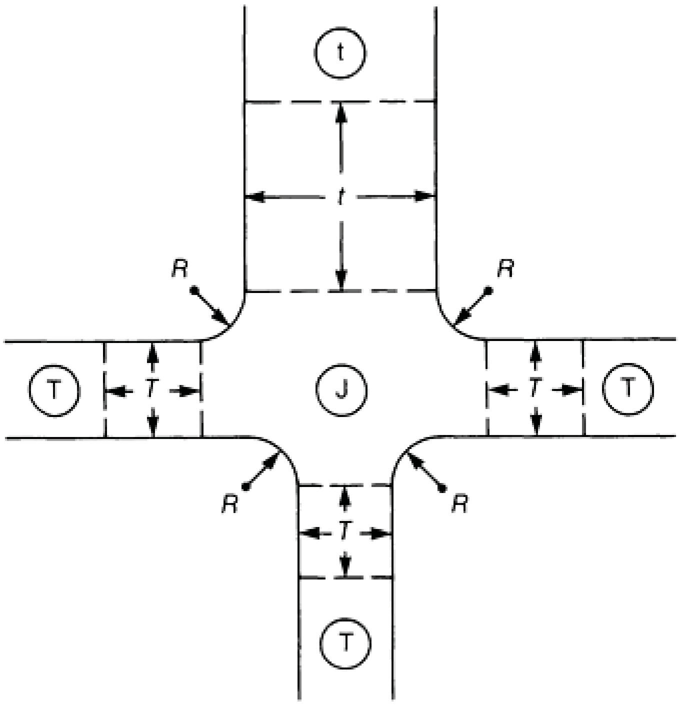

Fig. 9 Model of X-section with three legs equal. See Fig. 10 for solidification sequences.

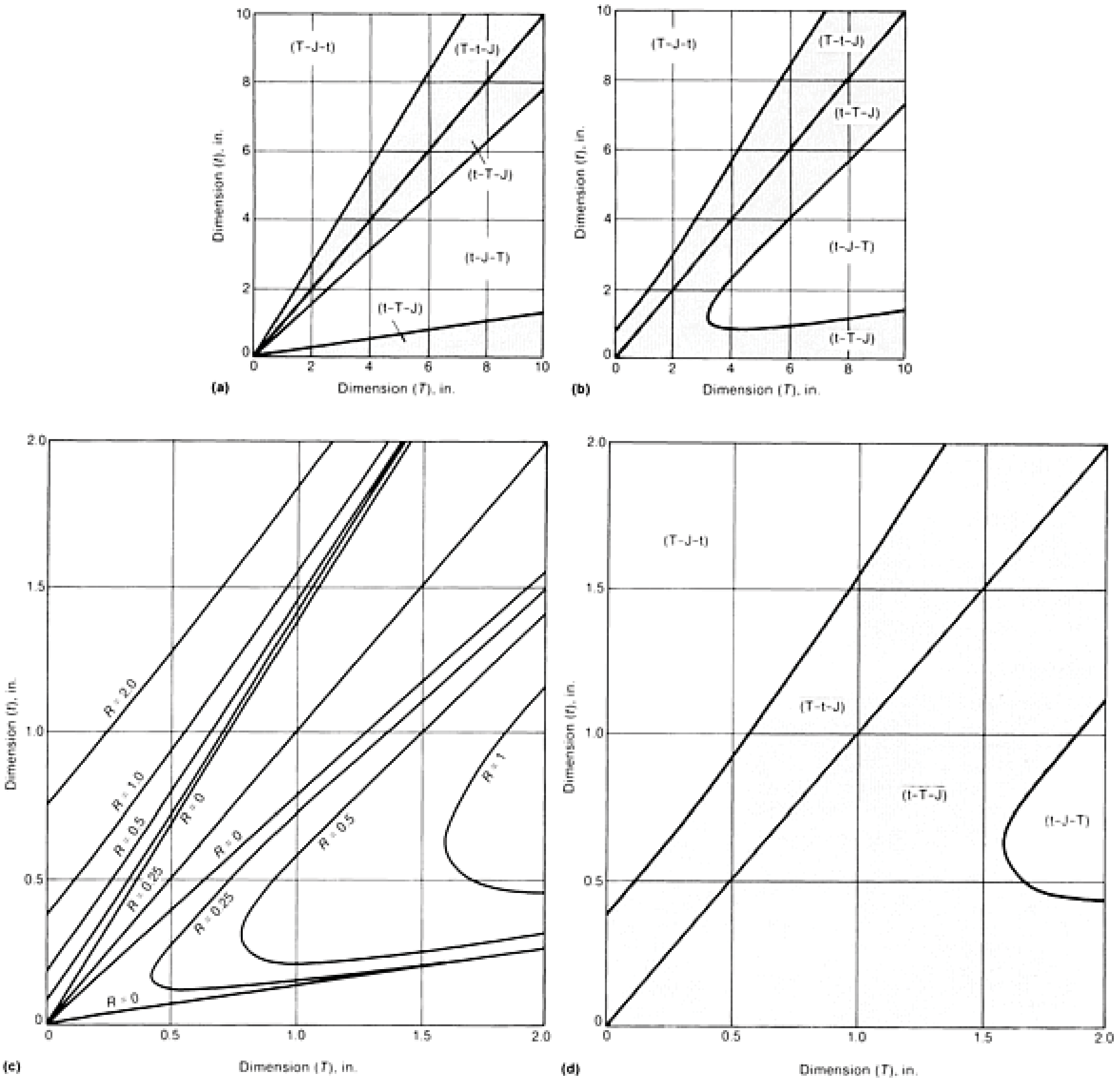

Fig. 10 Solidification sequence curves for X-section with three legs equal. (a) $R = 0$. (b) $R = 2$. (c) Composite of design curves for various fillet radii. (d) One segment ($R = 1$) of the composite design curve shown in (c).

The lower right-hand portion of the curve represents the case in which a T-section is to be chilled by the addition of a thin plate. In this case, if the thin plate is too small, it does not provide sufficient surface area to chill the T-junction, thus causing it to solidify before the plates making up the T-junction. This is the t-T-J sequence portion near the horizontal axis of the curve. Only when the t plate provides sufficient surface area to chill the T-junction can the t-J-T sequence be achieved. Finally, as the thinner plate continues to increase, the t-T-J sequence is again encountered.

When one of the legs that make up the X-section has a different dimension than the remaining three legs, two separate casting moduli equations must be used. For the case in which the odd plate labeled t on Fig. 9 is larger than the other three plates labeled T, the following casting modulus equation applies for the resulting J junction:

$$\frac{Volume}{Surface\ \text{Area}} = \frac{2t^2 + 3T^2 + 3RT + Rt + Tt + 0.8584R^2}{5T + 3t + 6.2832R} \qquad \textbf{(Eq 5)}$$

Equation 5 will apply to the upper left corner of the resulting design curves in which *t* is greater than *T*. For the case in which the dimension *T* is greater than *t*, the following casting modulus applies for the J junction:

$$\frac{Volume}{Surface\ \text{Area}} = \frac{6t^2 + 3T^2 + tR + 3Rt + 0.8584R^2}{11T + 7T + 6.2832R} \quad \textbf{(Eq 6)}$$

The effect of adding a 2 in. radius to this X-section is identical to that seen on the T-section previously discussed. This can be demonstrated by comparing Fig. 10(a) and 10(b). Design curves for various fillet radii are shown in Fig. 10(c) and 10(d).

L-Sections

The third basic shape of importance to design engineers is the L-section. The model of an L-section is shown in Fig. 11. Two different radii are used to describe this section: internal radius *r* and external radius *R*. Because two different radii are required in describing this type of section, two design cases arise: one in which *R* is greater than *r* and one in which *R* is less than *r*.

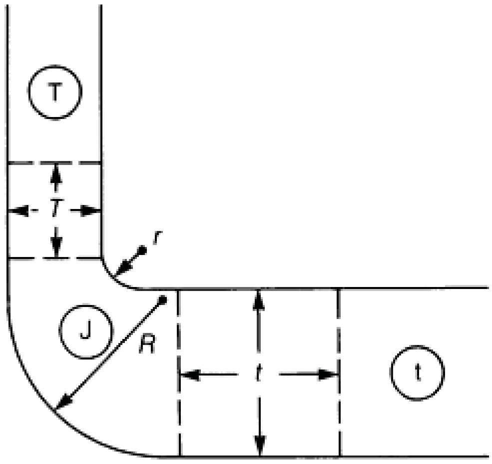

Fig. 11 Model of L-section for $R > r$. Compare with Fig. 12. See also Fig. 13 for solidification sequences.

For the case in which the internal radius *r* is less than the external radius *R*, an L-section similar to that shown in Fig. 11 will result. For cases in which *r* is greater than *R*, L-sections of the form shown in Fig. 12 will result.

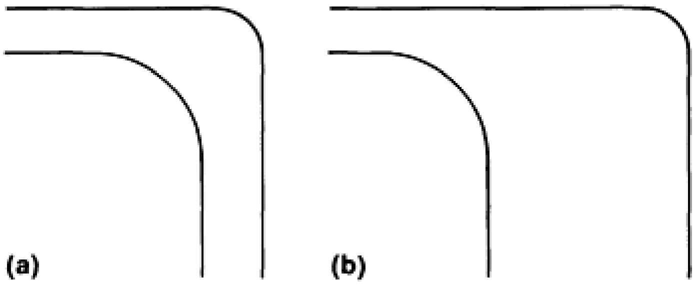

Fig. 12 Two L-section designs that can occur when $R < r$. (a) L-section has a higher modulus than the plates when plate thicknesses are nearly equal. (b) Plate thicknesses are very unequal; the modulus of the L-section is less than that of the thick plate.

External Radius Greater than Internal Radius. The casting moduli equations for the J- or L-junction in which $R > r$ are also a function of the design parameters being considered, and four equations must be used. For $R > t + r$ and $R < T + r$, the casting modulus of the junction is:

$$\frac{Volume}{Surface\ \mathrm{Area}} = \frac{T^2 + t^2 + TR + tr + 0.2146r^2 - 0.2146R^2}{t + 3T + 1.5707r + 1.5707R} \qquad \textbf{(Eq 7)}$$

For $R > T + r$ and $R > t + r$, the casting modulus of the junction is:

$$\frac{Volume}{Surface\ \mathrm{Area}} = \frac{T^2 + t^2 + RT - tr + 0.2146r^2 + 0.2146R^2}{t + T + 2.8584R - 0.4292r} \qquad \textbf{(Eq 8)}$$

For $R < T + r$ and $R < t + r$, the casting modulus of the junction is:

$$\frac{Volume}{Surface\ \mathrm{Area}} = \frac{T^2 + t^2 + Tt + rt + rT + 0.2146r^2 - 0.2146R^2}{3T + 3t + 2.8584r - 0.4292R} \qquad \textbf{(Eq 9)}$$

For $R > T + r$ and $R < t + r$, the casting modulus of the junction is:

$$\frac{Volume}{Surface\ \mathrm{Area}} = \frac{T^2 + t^2 + Rt + Tr + tT + 0.2146r^2 - 0.2146R^2}{3t + T + 1.5707R + 1.5707r} \qquad \textbf{(Eq 10)}$$

Although the sequencing curves for $R > r$ shown in Fig. 13(a) and 13(b) seem complex, the complexity is easily understood by remembering that both the internal and external radii (r and R, respectively) are held constant on any given graph. The first unusual feature of graphs of this type is the forbidden zone, that is, the dark area in the lower left corner of the graph. In this area, L-sections using the radii combinations given in the figure caption are impossible, and the internal radius punctures the external radius (Fig. 14a).

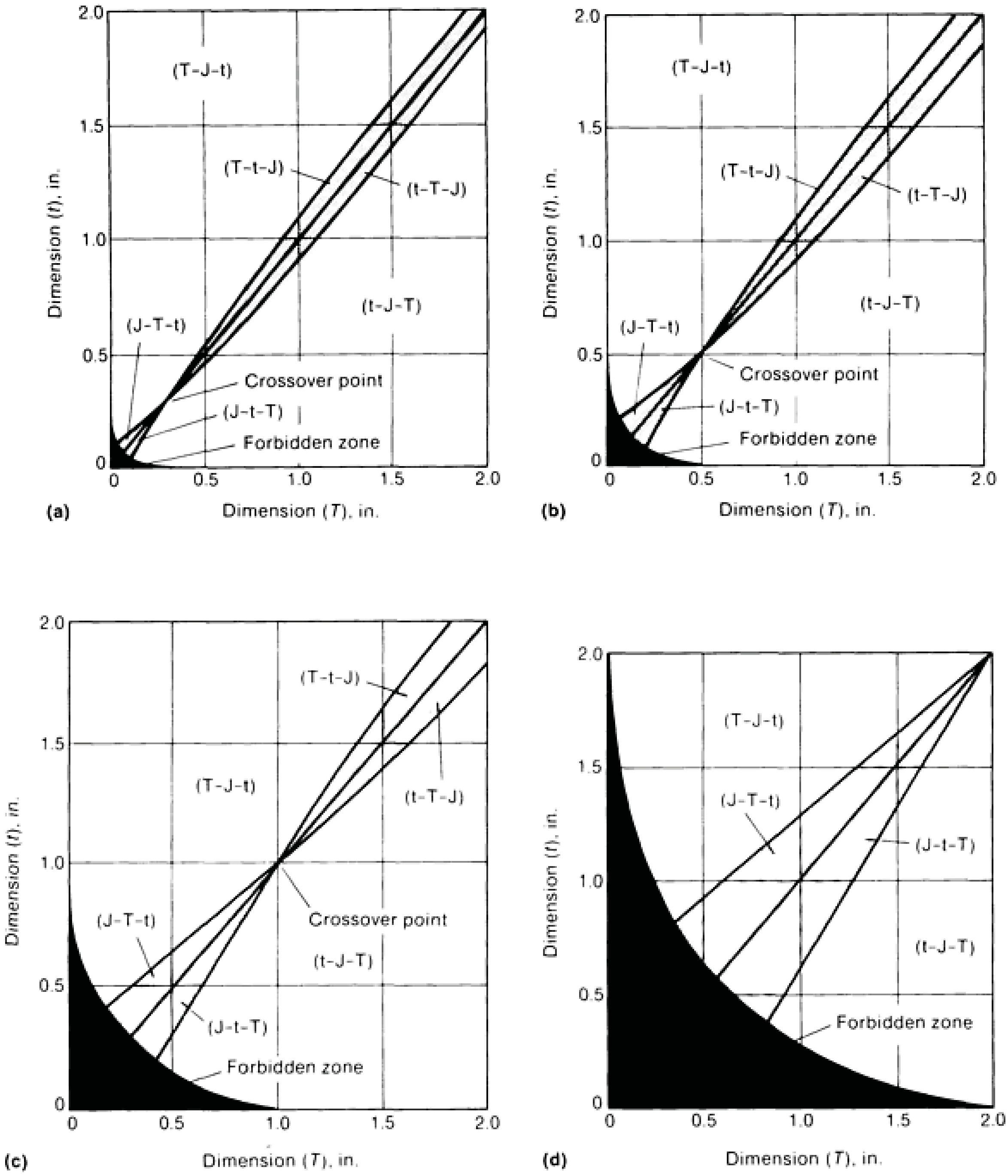

Fig. 13 Solidification sequence curves for the L-section shown in Fig. 11 with $R > r$. (a) $r = 0.25$, $R = 0.5$. (b) $r = 0.5$, $R = 1$. (c) $r = 1.0$, $R = 2.0$. (d) $r = 2.0$, $R = 4.0$.

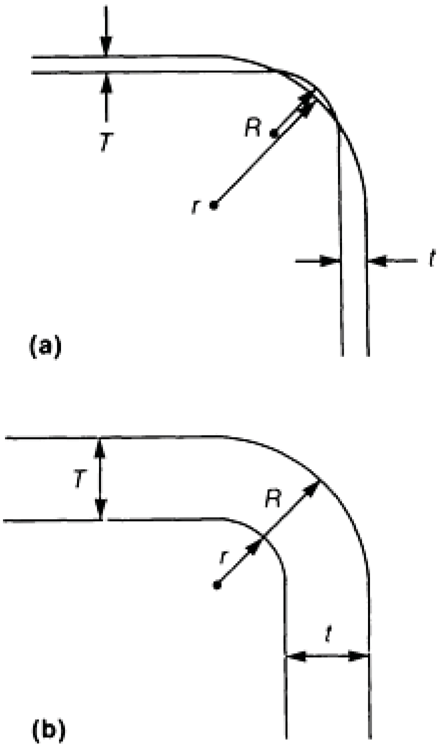

Fig. 14 L-section designs that fall in the forbidden zones of Fig. 13. (a) Internal radius *r* punctures external radius *R.* (b) Crossover point occurs when moduli of all the components are equal--in this case at $t = T = 0.25$, as shown in Fig. 13(a).

Another unusual feature of these curves is the crossover point, which in Fig. 13(a) occurs at $t = T = 0.25$. At this point, the casting moduli of all the components of the L-section (t, T, and J) are equal. This occurs because a uniformly thick plate results from these particular design conditions, as shown in Fig. 14(b). The crossover point always occurs when $t = T = (R - r)$ for L-sections in which $R > r$. The effects of increasing the radii can be seen by comparing Fig. 13(a) with 13(d).

External Radius Less Than Internal Radius. If the external radius *R* of an L-section is designed to be less than the internal radius *r*, completely different sequencing curves result. The simplified geometry of L-sections in which $r > R$ also considerably simplifies the casting modulus of the resulting J- or L-junctions. Because of the geometry, only the following casting modulus equation is required:

$$\frac{Volume}{Surface\ \text{Area}} = \frac{T^2 + t^2 + rT + rt + Tt + 0.2146r^2 - 0.2146R^2}{3T + 3t + 3.5707r - 0.4292R} \qquad \textbf{(Eq 11)}$$

Curves for L-sections with two such $R < r$ combinations are shown in Fig. 15. No crossover point occurs, nor does the curve contain a forbidden zone. The reasons for this can be determined by noting the features of such L-section designs (Fig. 12).

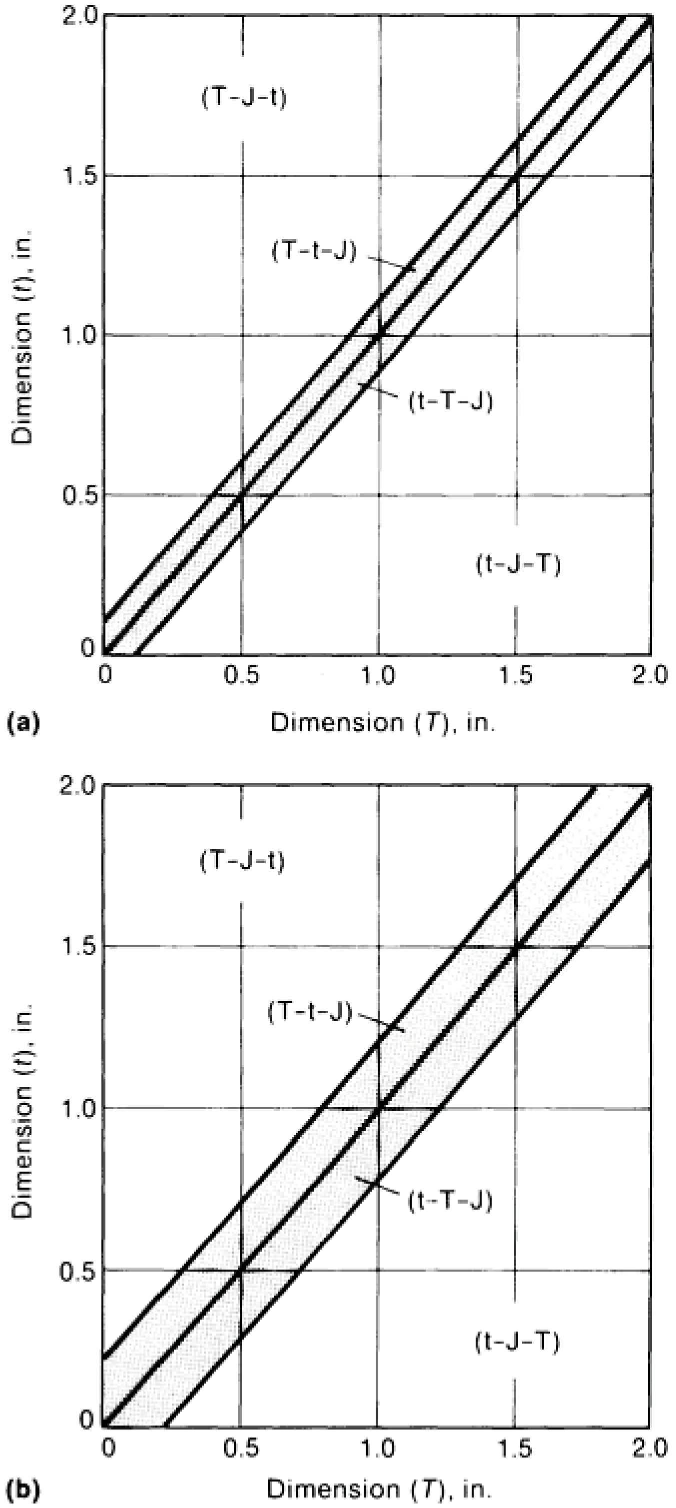

Fig. 15 Solidification sequence curves for L-sections with $r > R$. (a) $r = 0.5$, $R = 0.25$. (b) $r = 1$, $R = 0.5$. Compare with Fig. 13.

Feeding

Solidification of Flat Plates. The L-, X-, and T-sections discussed to this point consist of a combination of plates and the junctions themselves. Any discussion of casting design must also consider the solidification of simple flat plates as well as their more complex junctions.

The solidification of metals does not occur as a flat moving front, but rather as a series of protuberances ranging in shape from cone points to very complex, branched shapes called dendrites. The complexity of these shapes is a function of the speed of growth of the front, the cooling rates involved, and the composition of the alloy. For the purposes of design, the nature of these shapes concerns the ability of metal to develop a feeding path through uniform flat plates or cylinders. Because these protuberances in most alloys of interest at commonly found growth rates and thermal gradients usually manifest themselves as dendrite-type shapes, they can provide a significant barrier to the continued flow of metal. This phenomenon can lead to shrinkage defects in castings because the feed metal supply cannot reach into the solidifying front at which the liquid-solid contraction is causing a feed metal demand. In particular, this effect influences casting design in the area of feeding distances.

In a simple plate having a constant thickness *T*, a set of solidification fronts will move from each of its surfaces until they meet at its centerline. However, as these fronts move together, their dendritic character begins to cause a blockage of the metal flow from a feeding path, which will result in some degree of shrinkage. This phenomenon has been quantified, and it has been determined that the ability of a riser to feed through a plate is very limited (Ref 1). Often, sound casting production can be achieved only for a few thicknesses along the plate even when chills are used. This is very important because long flat plates will require extensive risering for this reason alone. This limited ability to feed can be overcome by simply reducing the tendency for the front closure to occur as a straight line. This is accomplished by using a plate whose cross section is not uniform in thickness but is continuously changing in thickness, such as the wedge casting discussed earlier.

Another way of accomplishing the same objective without changing the geometry of the plate is to alter the thermal shape of the casting through the use of an insulating or chilling material to change the rate of heat extraction. Still another way of accomplishing feeding through an extensive constant plate thickness is to create a series of feeding paths close to each other.

Consider a circular flat plate with a single riser at the center of the plate, as shown in Fig. 16(a). If the feeding distance creates a problem, multiple feeding paths could be considered as a solution. The design of feeding paths involves the development of shape geometries that permit solidification to be directed to a portion of the casting that can be easily fed by a riser.

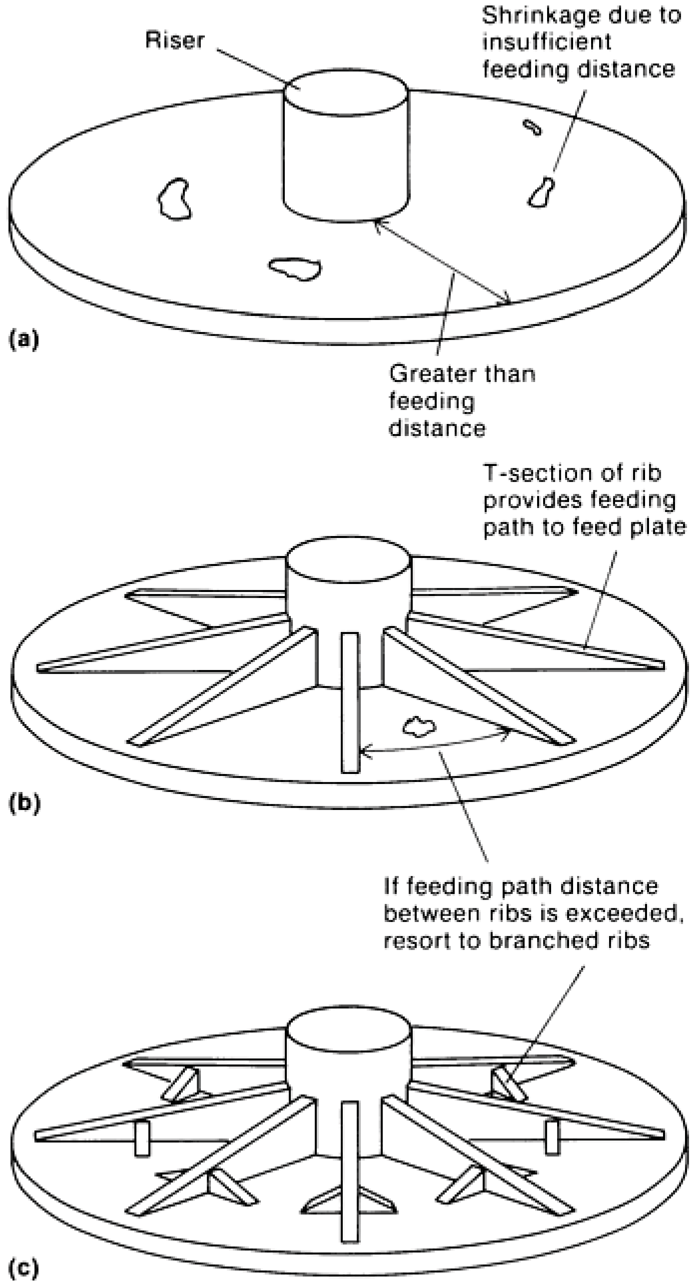

Fig. 16 Feeding path design considerations. (a) Circular flat plate with a single riser. (b) Addition of wedge-shaped ribs to ensure proper solidification. (c) Branched ribs to overcome feeding problems at the circumference of the plate.

For this example, it is necessary to create a feeding path to the center of the plate where it can be fed by the riser. If the addition of radial ribs presents no problem, wedge-shaped ribs could be added, with the taper increasing as the rib nears the center of the plate (Fig. 16b). Because feeding distance is a problem only for continuous-dimensioned flat plates if the distance between these ribs does not exceed the feeding distance for the plate thickness, the ribs will ensure feeding of the plates to soundness. Because the ribs themselves are tapered to create a path to the riser, they should also be sound (free of shrink). If feeding distance again becomes a problem at the outer circumference of the circular plate, the ribs could be branched to ensure that the feeding distance for the flat plate is maintained (Fig. 16c). If the geometry of the rib causes difficulty with the design of the resulting casting, the same idea could be applied through the use of insulating or chilling materials to create the same effect thermally without the addition of the added metal of the ribs. However, because the use of molding materials to create the needed feeding path would no doubt increase the cost and complexity of the solution, it should be avoided if possible.

Solidification of Cylinders. A restriction of feeding distances similar to that in plates also occurs in cylinders. Once again, this can be overcome through a change in the thermal shape by developing a cone shape either geometrically or through the use of chilling or insulating materials. Cylinders, however, do create a new condition.

The new condition of concern is the junctions produced by the intersection of a cylinder and other cylinders or plates. If the cylinders are hollow, it is not necessary to consider them separately, because these conditions can be visualized as L- or T- sections merely revolved about an axis. However, a separate geometric case develops when the cylinder is solid. Figure 17 shows an example of such a case as well as the resulting design curve. On this curve, the solidification sequence is either D-J-T or T-J-D, and no case exists in which the junction J is the last to freeze. For such a junction, either the cylinder acts as a chill for the junction or the plate tends to act as a chill dependent on the cylinder diameter *D* and the plate thickness *T*. Thus, such intersections are straightforward and should cause little problem for designers or casting engineers if the feeding distance relationships and other thermal shape factors for promoting directional design are followed.

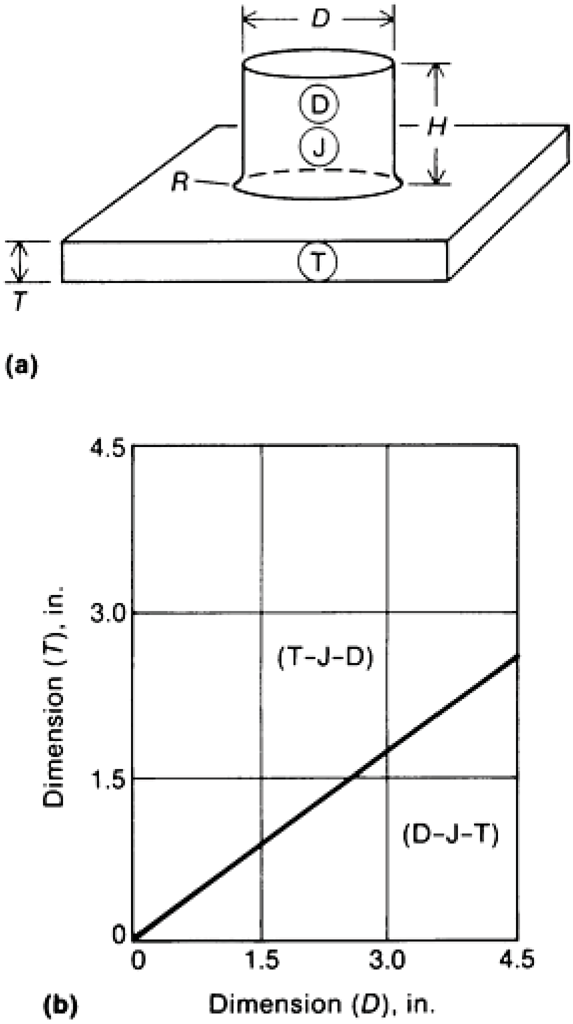

Fig. 17 Example of a design using a solid cylinder (a) and the solidification sequence curves for such a design (b).

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1. R.A. Flinn, *Fundamentals of Metal Casting,* Addison Wesley, 1963

Changing Thermal Shape

Thus far, this article has considered the designs of plates, cylinders, and T-, X-, and L-sections, in which all of the components of the mold extract heat uniformly. However, there are many instances in casting manufacture in which this is not the case. Such situations occur during the normal course of the casting process and in some cases are done intentionally to change the solidification sequence--for example, the use of a core or a chill.

Use of Cores and Chills. Cores are often used in casting, but their effect on the solidification sequence of a section depends on the relative heat extractive capability or heat diffusivity differences between the mold and core components. If the heat extractive character of the core components is greater than that of the mold components, the core will tend to act as a chill. This occurs because heat is removed more efficiently from the portions of the casting in contact with the chill than from those in contact with mold components.

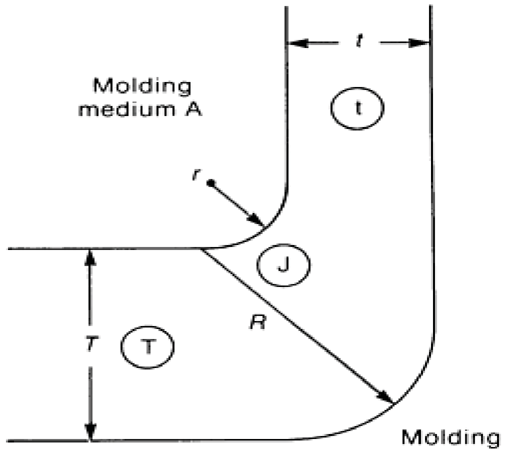
More commonly, the diffusivity of the core when made of resin bonded silica sand is lower than that of the green sand mold components, and the core acts as an insulator with respect to the mold components. It must be remembered that the relative heat extractive capacity of the various mold components determines the resulting solidification sequence. The results shown here are independent of the actual mold and cores being considered because the solidification sequence is important in casting design, not the time required for an individual portion of the shape to solidify.

Only in a few rare cases, as in continuous casting and slush casting (the manufacture of hollow castings through decantation of unsolidified liquid), is the actual time for solidification important. In these cases, the actual position of the solidification front at a particular time is important. This is not true for most casting design situations, in which only the sequence of events is important because the order affects the formation of a feeding path. However, the actual time required for an individual component to solidify is usually relatively unimportant if its position in the overall solidification sequence can be determined.

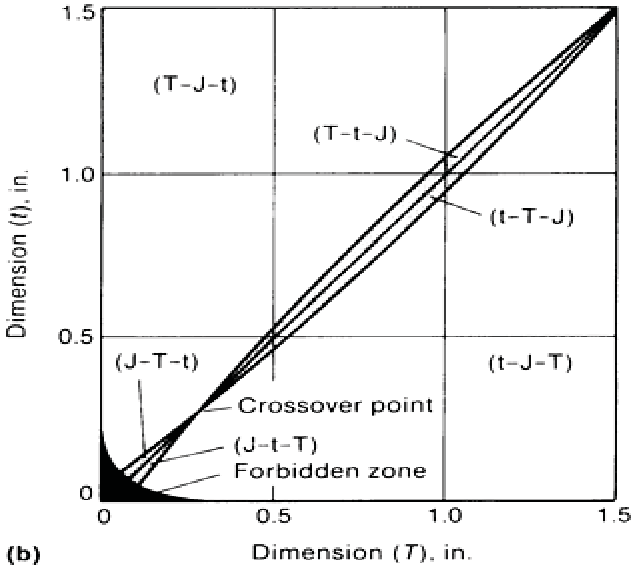
Because of this comparative unimportance of the actual solidification time of a given component, only the relative ratios of the thermal diffusivities of the two materials involved, rather than the actual diffusivity of each, need be considered in the design curves. Thus, to understand the major effects on the design of T-, X-, and L-sections, only two cases must be considered: one in which one mold component is insulating with respect to the other, and a second in which one component has a chilling effect compared to the other. By convention, the diffusivity ratio is always defined as the ratio of a material divided by the diffusivity of the mold. For example, in a green sand mold, the ratio is the diffusivity of the non-green sand component and the diffusivity of green sand, and for a permanent mold application, the ratio equals the diffusivity of a given component/diffusivity of die material.

If one mold component is insulating with respect to the mold material, the diffusivity ratio would be less than 1. A common condition of this type exists for the case in which a resin bonded solid sand core is placed in a green sand mold. The diffusivity ratio would be approximately 0.85 for this case. However, as stated above, the actual materials involved are relatively unimportant provided the same diffusivity ratio exists; the principal concern is the ratio of diffusivities rather than their actual values.

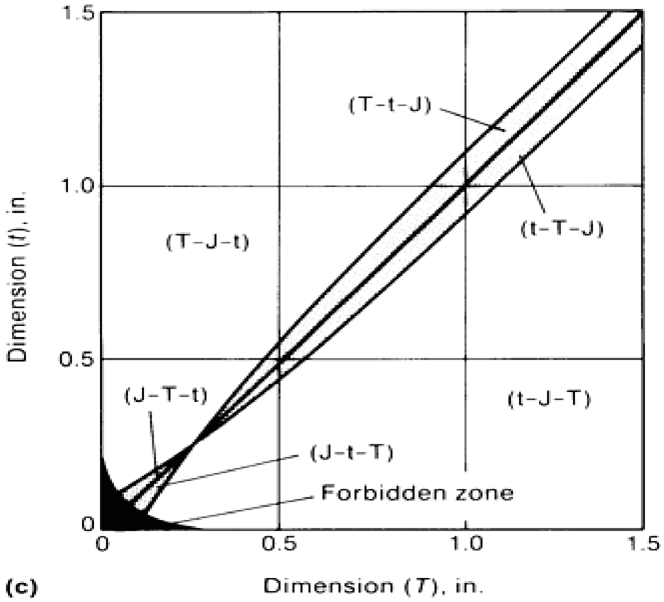
L-Sections. Before discussing the design curves for L-sections, it is important to consider the geometric consequences of such placements. An L-section is shown in Fig. 18(a). In such a section, there are two possible positions, A and B, that might be occupied by the insulating material. The basic difference between these two possible placements has to do with the amount of casting surface area exposed to each. For placements of insulation material in the inner corner (the A position), less area at the J-junction is exposed to the insulation material per unit volume than is exposed along the plates making up the section. This is important because one might expect the placement of insulation material along a junction to slow the solidification of the section.


t
Molding medium A
t
r
J
R
T
T
Molding medium B

(a)


1.5
(T-J-t)
(T-t-J)
1.0
(t-T-J)
Dimension (t), in.
0.5
(J-T-t)
(t-J-T)
Crossover point
(J-t-T)
Forbidden zone
0
0
0.5
1.0
1.5
Dimension (T), in.

(b)


1.5
(T-t-J)
1.0
(T-J-t)
(t-T-J)
Dimension (t), in.
0.5
(J-T-t)
(t-J-T)
(J-t-T)
Forbidden zone
0
0
0.5
1.0
1.5
Dimension (T), in.

(c)

Fig. 18 Model for an L-section (a) cast using two different molding materials A and B. (b) Solidification sequence model for L-section shown in (a) in which the insulating material is in the A position; r = 0.25, R = 0.5, diffusivity of mold material A = 2, diffusivity of mold material B = 1. (c) Baseline curve for comparison with Fig. 18(b), 19, 20, and 21 in which r = 0.25, R = 0.5, A = 1, and B = 1 where insulating materials are the same for positions A and B. See also Fig. 19, 20, and 21.

However, when the resulting L-section design curve (Fig. 18b) for this situation is observed, the exact opposite seems to be the case; that is, there are far fewer designs in which the junction solidifies last. This occurs because in position A the material extracts heat differently from the junction than the material along its outer area (position B). Because a greater percentage of surface area is contacted by a material in position A along the plates making up the L-section than from the junction itself, the plates are insulated to a greater degree than the junction. This means that insulation material placed in the A position tends to act as a chill from the point of view of the junction with respect to the plates making up the section. This occurs because a greater effect of insulation is experienced by the plates due to the increase in surface area exposed to the insulation material than by the junction. This results in a slowing of solidification of the plates more than its effect on the junction. Note that there are fewer designs in which J solidifies last in Fig. 18(b) than in Fig. 18(c), in which the mold (insulating) materials are the same for the A and B positions.

A similar apparent reversal of the expected effect when a chilling material is placed in the A position of an L-section can be seen in Fig. 19 for a relative diffusivity ratio of 2.0. Once again, the chill has a greater effect on the plates making up the L-section than on the junction itself. Such chill materials, when placed in the A position, tend to act as insulation materials from the point of view of the L-section. That is, because the plates are chilled to a greater degree than the junction due to the exposed surface area to the chill, chill placement in the A position creates more designs in which the junction tends to be the last portion to solidify, as can be seen in Fig. 19.

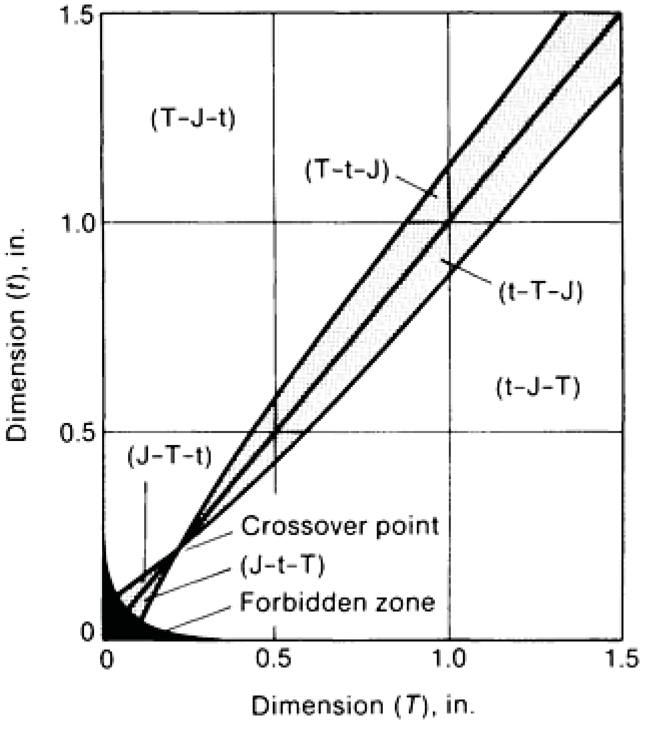


Fig. 19 Another solidification curve for the L-section shown in Fig. 18(a) in which a chill has been placed in the A position. In this case, r = 0.25, R = 0.5, A = 2, and B = 1 . See also Fig. 18(b) and 18(c), 20, and 21.

If material having an insulation character is placed in the B position of an L-section, it contacts a greater amount of surface area to volume in the junction than is contacted by the plates making up the section; the result of this is the reverse of that discussed for materials placed in the A position. This placement is illustrated in Fig. 20. Because the insulation effect is greater in this case on the junction due to the greater surface area contact, it creates more designs in which the L-junction solidifies after the plates. The effect of a chill placed in the B position can be seen in Fig. 21. It is clear from Fig. 18 that, because the chill affects the junction to a greater degree than the plates, the resulting design curves contain more designs in which the junction is the first to solidify. In addition, a radius in the A position placements tends to increase the area in contact with materials in the A position. However, external radii tend to lessen the surface area in contact with a material in the B position.

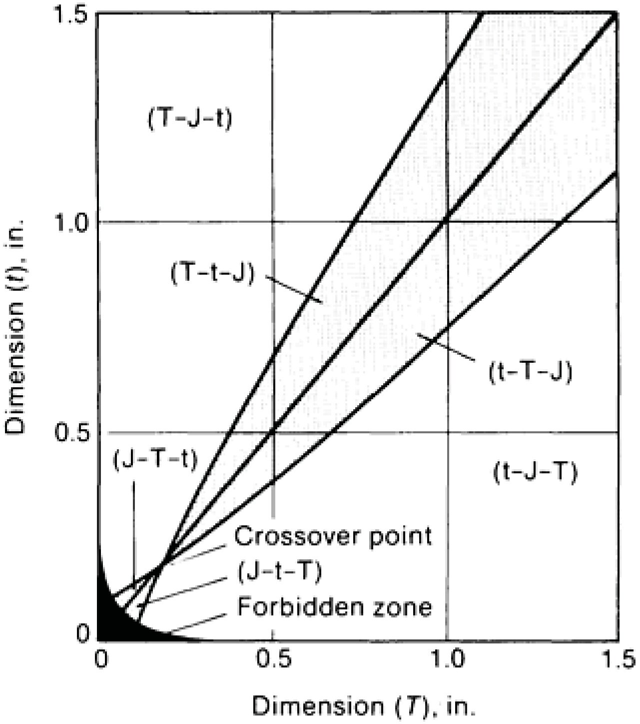


Fig. 20 Another solidification curve for the L-section shown in Fig. 18(a) in which the insulating material has been placed in the B position. *r* = 0.25, *R* = 0.5, A = 1, and B = 0.85. See also Fig. 18(b) and 18(c), 19, and 21.

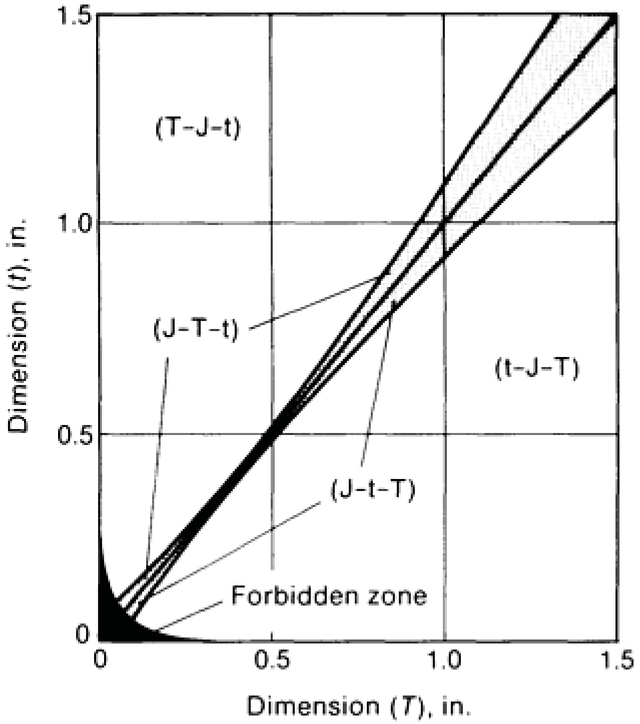


Fig. 21 Another solidification curve for the L-section shown in Fig. 18(a) in which a chill has been placed in the B position. r = 0. 25, R = 0.5, A = 1, and B = 2. Note that there is no crossover point in this figure. See also Fig. 18(b) and 18(c), 19, and 20.

T-Sections. In the case of a T-section, there are three potential positions in which insulating or chilling materials can be placed, namely, positions A, B, and C, as can be seen in Fig. 22. The T-shape causes several interesting effects. The first of these is similar to that observed for the L-sections. Materials placed in either the A or B position have a greater influence on the plates making up the section than on the T-section itself. Similarly, material in the C position has a greater influence on the solidification of the T-junction than on the plates making up the section.

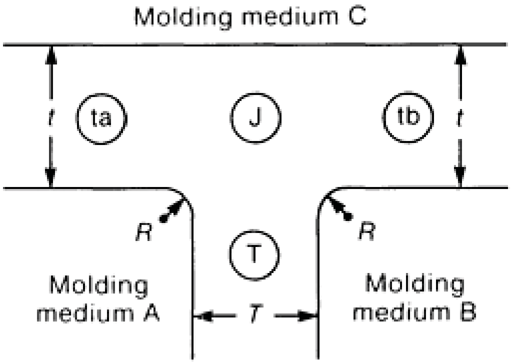


Fig. 22 Model of a T-section cast using three different mold materials. See Fig. 23, 24, and 25 for possible solidification sequences.

These effects are similar to those discussed for the L-sections, but because of the particular geometry involved in a T-section, several others also occur. For example, when the material in the C position is different from that in the A and B positions, the effects on the plates ta and tb are indistinguishable (Fig. 23). If the materials in the A and B positions are different, there will be a difference in the solidification of the two halves of the cross plates ta and tb. Figure 24 illustrates this effect, in which each of the plates ta and tb are shown to provide an independent section on the design curve. This effect is a result of the imbalance of the heat extraction across the intersecting plate labeled *T* in Fig. 22, and it is also evident in the use of chilling as well as insulating materials (Fig. 25). In addition, if A and C or B and C are similar materials, an imbalance still exists across the intersecting plate of the T-section, resulting in a design curve in which the plates ta and tb separate into individual effects (Fig. 24 and 25).

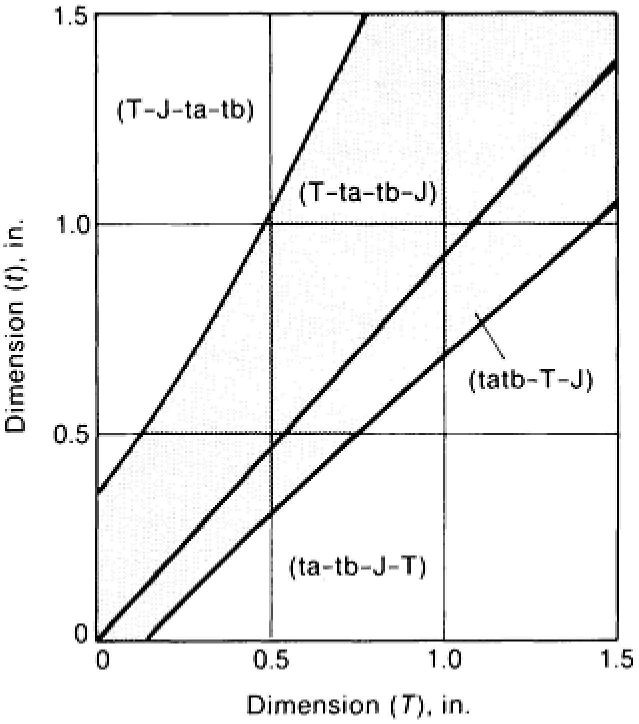


Fig. 23 Solidification sequence curve for T-section shown in Fig. 22 with R = 0.5, A = 1, B = 1, and C = 0.85. Note that in one case (area marked tatb-T-J), ta and tb solidify at the same time. See also Fig. 24 and 25.

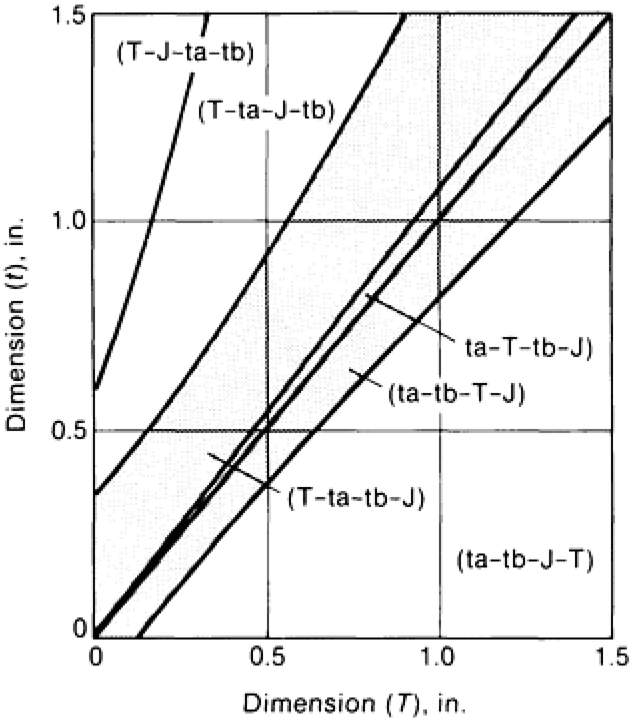


Fig. 24 Solidification sequence curve for T-section shown in Fig. 22 with R = 0.5, A = 1, B = 0.85, and C = 1. See also Fig. 23 and 25.

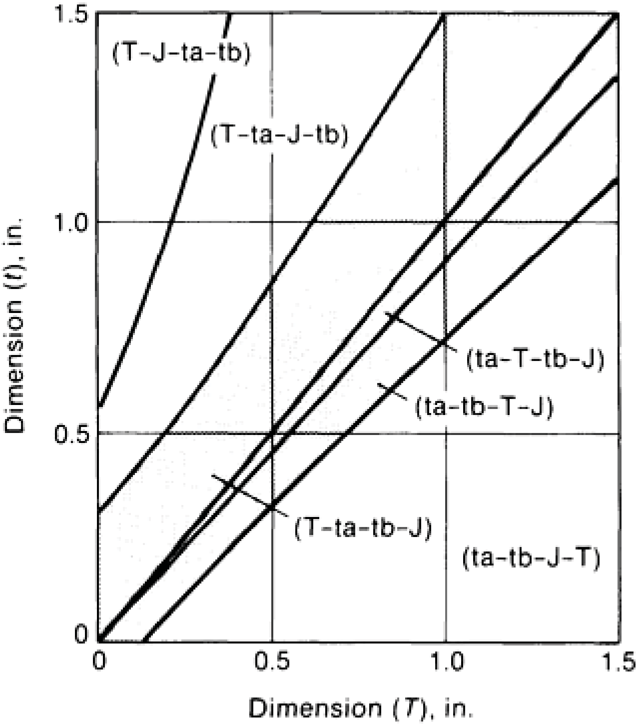


Fig. 25 Solidification sequence curve for T-section shown in Fig. 22 with *R* = 0.5, A = 0.85, B = 1, and C = 0.85. See also Fig. 23 and 24.

X-Sections. In the case of X-sections, a geometry-related effect exists. When an insulating or chilling material is placed in a single position, it influences two of the plates but not the other two plates. It also has an effect similar to placements on L-sections in their inner corner in that the material has a greater influence on the plates making up the section than on the X-section itself. This means that the effects are similar to those seen in L-sections discussed previously; chills tend to act as insulating materials from the point of view of the X-section. In addition, diagonal placements across the section cause a matched effect on all of the plates making up the section.

Therefore, when mold materials of different diffusivities are employed, the results can be predicted, but geometric effects can often produce results that may not be obvious. Thus, to predict the results of a given set of conditions, one must consider the effects very carefully. However, the amount of contact area of each portion of a section in direct contact with a chill or insulator plays a significant role in the eventual solidification behavior.

Computer-Aided Casting Design

Computer-aided design and manufacture (CAD/CAM) systems are becoming increasingly prevalent in industrial design, and their use offers both opportunities and problems for casting designers. These systems greatly reduce the cost of the engineering and design time involved in preparing engineering drawings. When using CAD systems, most designers still use primarily straight lines and chordal parts of circles. This is unfortunate, because the true power of such systems (as related to casting design) would be the full use of the superior design capability of such shapes as sines and parabolas. Designers should make the effort to consider such shapes for both improved stress distribution and better casting designs.

Another problem with the use of CAD/CAM systems is that many companies are using wireframe systems rather than the newer solid modelers. This situation will probably not change for some time, because solid modeler CAD/CAM systems require the designer to work with three-dimensional shapes instead of the more familiar two-dimensional features. Further, the thought process taught to designers is not one of removing area from an existing shape, as required by solid modelers, but rather of developing a shape through a construction procedure. Thus, even though solid modelers are better algorithms for casting design, it is unlikely that they will be extensively used in the near future.

Because wireframes seem to be the preferred technique for the present, designers must recognize and deal with the problems of this algorithm. Wireframe algorithms were designed to create pictures and graphic representations of the actual three-dimensional shape, not necessarily to produce shapes of true three-dimensional integrity. Until such three-dimensional representations of the desired shape are attempted to be used to create pattern equipment, the problem with these algorithms may not even be recognized. Because the shapes are not truly three dimensional, nonmatches of straight lines and arcs can go unnoticed until the pattern equipment attempts to use the CAD information to cut the pattern. This problem is recognized, and software is available to solve it and similar problems; but such software requires transfer of data from computer-aided design to pattern cutting, which is often difficult since data formats have not been standardized but are computer and software dependent.

If the full cost savings available through CAD-generated pattern equipment is to be realized, improved wireframe algorithms or solid modelers that eliminate these kinds of problems must be developed and used widely. There is also a significant need for better software that truly allows the error-free passage of CAD/CAM data to other computers and other software.

One very effective computer tool is available that uses CAD casting designs to simulate the solidification of a casting through solidification modeling. The developed algorithms of such simulations can be divided into three basic types:

- Those based on classical heat transfer equations
- Those based on finite-element methods or finite-difference methods (FEM or FDM), which are iterative techniques based on classical heat transfer
- Those based on ratios of surface area to volume, as discussed by Kotschi and Plutshack (Ref 2)

Heat Transfer Analysis. The first of these approaches involves attempts to write a single set of heat transfer equations to describe a solidification problem. Because of the complexity of the differential equations involved, this approach has not led to substantial developments. Further, many of the differential equations required for such a solution cannot be solved without significant simplification of the equations; therefore, the potential for this technique is limited until such techniques can be developed. Solutions to these problems have been attempted, but the sheer magnitude and complexity of the equations and iterations required even for supercomputers holds little hope of a viable solution of economic interest to industrial designers. This leaves the two remaining approaches, both of which have provided workable and usable algorithms to solve this problem.

FEM and FDM Analysis. Use of either the FDM or FEM technique involves the development of a three-dimensional grid. The grid blocks are then used as a set of differential elements to calculate the heating and cooling effects. The heat content of each element and its relationship to all the other grid elements in its influence are calculated. In this way, a solution of the entire shape is developed through a series of iterations as a function of time.

Selection of the grid points is critical to the accuracy of FEM or FDM solutions. The greater the accuracy desired from such calculations, the finer the mesh of the required grid. However, the cost of the solution increases dramatically as the number of grid points increases. Thus, to reduce the cost of such solutions, grid points are usually increased in areas of interest or areas having a significant effect on the solution. Similarly, the number of grid points is reduced in areas deemed less significant to the final solution. This has been a major problem in the extensive use of such systems in industry.

Unfortunately, the high-accuracy FEM or FDM systems employed to date have had no grid selection algorithm; therefore, selection is done by personnel skilled in this selection process and in FEM or FDM techniques. Such talent is not readily available, and even when it is, the expenditure of several weeks by several individuals on such a problem is hardly cost effective, especially since this is only 1 of 10 to 15 solutions required to develop an optimum manufacturable casting design.

An example of the cost of finite-element and finite-difference methods is provided by the analysis recently performed on a three-dimensional section of an engine block. A single cylinder (one of six in the complete engine) and its associated valve cavities were studied. Development of the grid and setup of the problem took four individuals a month. The actual analysis required 8 h on a supercomputer. With setup and grid development costs of $10,000 and computer time costs of $25 per minute (a very low estimate), the cost of a single analysis was $22,000. Considering that ten or more analyses may be required to obtain the optimal design, it can be seen that such analyses are not economically feasible for most companies.

The complexity of such problems, and therefore the cost of the solutions, can be reduced by simplifying the problem through, for example, the use of fewer grid points. In this simplified form, particularly in the case of only two-dimensional slices through a critical area, the computer overhead can be greatly reduced, and economically useful solutions can be found.

An example of such software using an FDM approach is the AFSolid Software available from the American Foundrymen's Society. This software analyzes only in two dimensions, incorporating a uniform pattern of grid points for ease of use, and it limits the number of grid points to 5000 as a maximum to hold down the iterative overhead. At the maximum number of grid points, the program can take approximately 15 to 20 min on a high-end desktop computer such as an IBM PS/2 model 80 with a math co-processor without including heat of fusion in the calculation; the program can take 2 h if heat of fusion is included. At this level of sophistication of both hardware and software, economically available answers are practical and cost effective. However, this type of software is of more value to foundrymen than to design engineers because it requires knowledge of the potential solidification problem to such a degree that it can be reduced to a two-dimensional problem.

Unfortunately, to assist design engineers at the drawing board or CAD station, three-dimensional solidification analysis software would be of more value, particularly if it were easily accessed from the CAD software. However, to go from two dimensions to three dimensions with the FDM or FEM approach, the complexity of the problem increases geometrically. For this reason, without substantial increases in hardware and software sophistication and speed, this approach will see only limited use in the future for the three-dimensional problem.

Volume-to-Surface-Area Ratios. Another algorithm was first proposed by Kotschi and Plutshack based on the use of volume-to-surface-area contour lines. These lines were shown to simulate the progression of solidification throughout the cross section of a two-dimensional slice of a solidifying shape. The importance of this approach is in the simplification of the algorithm and the resulting higher speed and lower cost for analysis. It must be remembered that, without low-cost analysis techniques, solidification simulation is of only academic interest. The method can also be applied to three-dimensional shapes with less increase in computer software overhead than with FEM or FDM techniques.

Software based on the use of the casting modulus contours suggested by Kotschi and Plutshack has been developed at the University of Wisconsin through a foundry consortium. This software, called SWIFT, holds much promise as a potential solution to the need for a three-dimensional solidification analysis that is useful to design engineers, but at present the marketing rights to the three-dimensional software are available only to consortium members. However, a two-dimensional system is being marketed, but is not available for MS-DOS or OS/2 machines. Most of the two-dimensional software packages of this type are currently running on VAX and Mini-VAX type machines.

An alternative software program developed for three-dimensional solidification analyses is SOLSTAR*. Although the algorithm is proprietary, the method is based on a type of FDM approach in which the time differential variable is eliminated from the model and each node is in some way compared with other nodes to determine the solidification sequence. The maximum capacity of SOLSTAR is 300,000 node points for a three-dimensional problem. Because of the simplification of the FDM approach, the computer running time for a 300,000 point simulation is reported to be 45 min on a system similar to the IBM PS/2 discussed above.

Only by simplifying the FDM/FEM models or by implementing new approaches can the computer overhead be reduced enough to provide economical solutions that can be used by the majority of the foundry and casting design industry. If the puristic FDM/FEM solutions are all that are available, the benefits of such techniques will affect only those corporations significantly large enough and requiring sufficient production quantities to afford them. This will of course change if supercomputers are available in the future at personal computer prices.

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2. R.M. Kotschi and L.A. Plutshack, An Easy and Inexpensive Technique to Study the Solidification of Castings in Three Dimensions, *Trans. AFS,* Vol 89, 1981, p 601-610

Note cited in this section

* SOLSTAR is a registered trademark of Foseco Ltd.

Mold Complexity

Casting solidification is the first major factor a designer should consider in reducing costs. However, there is a second major factor that should also be considered, namely, the mold complexity factor. This is usually related to a requirement for an excessive number of cores. *Thus, the fourth rule for economical casting design is to eliminate as many design features requiring cores as possible.*

The use of cores in the casting process provides a unique feature that is not available in most other methods of manufacture, yet each core required adds to the final casting cost. Thus, only those cores that are absolutely necessary for producing the desired shape should be used if design is to be directed toward lower cost castings.

The first principle that must be understood to eliminate cores is the method of mold manufacture. Even investment and expendable pattern (lost foam) molds require that the molds or tooling used to make the patterns be fabricated as separate pieces or mold halves. For example, in sand processes, a boxlike device called a flask is set over the pattern and filled with sand. The sand is hardened either through chemical or mechanical means, and the pattern is then removed. The pattern must be removed by drawing it away from the mold in a direction perpendicular to the parting line; therefore, the design factors related to this common practice must be considered by the design or casting engineers.

The required factor that assists pattern withdrawal is called draft. As can be seen in Fig. 26, the need to withdraw the pattern from the mold requires that some taper or draft be added to the pattern. Although pattern draft is usually not a problem, the requirement of removing the pattern by withdrawing it in a direction 90° from the parting line does restrict total design freedom if casting costs are to be minimized.

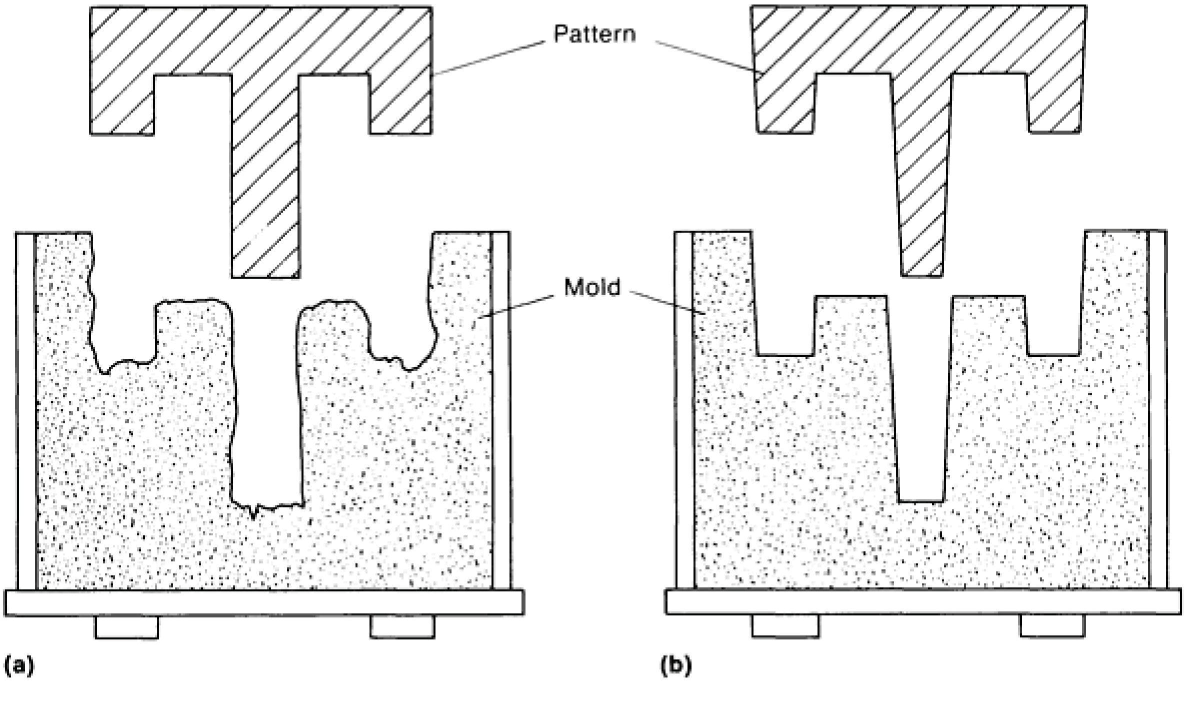


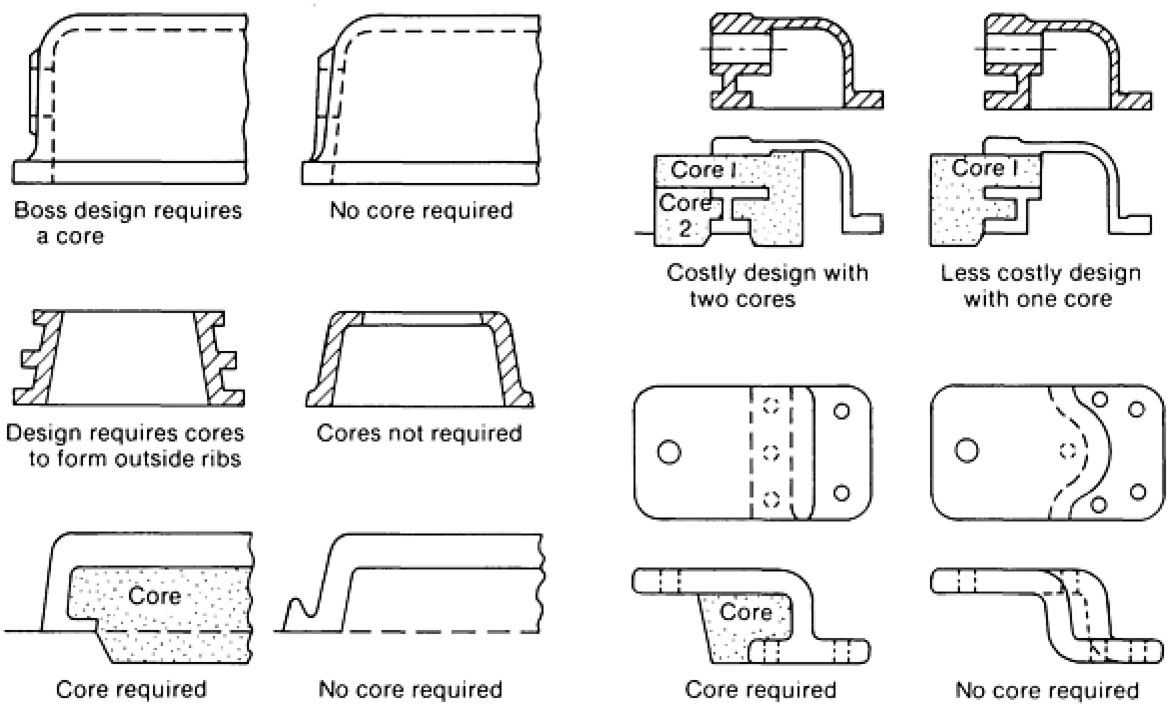
Fig. 26 Use of draft to facilitate withdrawal of the pattern from the mold material. (a) Lack of draft causes damage to the mold when the pattern is removed. (b) Ample draft allows easy pattern removal.

Because the pattern is to be withdrawn straight out of the mold, no protrusions that restrict this movement can be allowed in the construction of the pattern. If the geometry of the part requires such protrusions, there are only two alternatives for the casting engineer:

- Use a loose piece that remains in the mold or core after the pattern is drawn and then is removed separately

- Provide a portion of the pattern that creates a cavity for the setting of a core to create the geometry

The first alternative has limitations in that sufficient room and access to remove the loose pieces must exist. Loose pieces can be used only in moderately low volume casting production because they limit productivity in high production. Furthermore, because of the added handwork and potential for mold breakage during extraction, the use of loose pieces can be expected to increase casting costs even in low production. The second alternative involves the addition of a core and therefore also increases casting costs. The problem and some proposed solutions to undercuts are shown in Fig. 27.



Boss design requires a core

No core required

Costly design with two cores

Less costly design with one core

Design requires cores to form outside ribs

Cores not required

Core required

No core required

Core required

No core required

Fig. 27 Restrictions to pattern removal, and some potential solutions.

Finally, because part geometry can require more complex patterns due to irregular parting lines, *the final rule for reducing casting costs is to design straight parting lines whenever possible*. This rule can be seen in practice in Fig. 28. Because much thicker patterns are required for offset parting lines, the cost of the pattern is also greater.

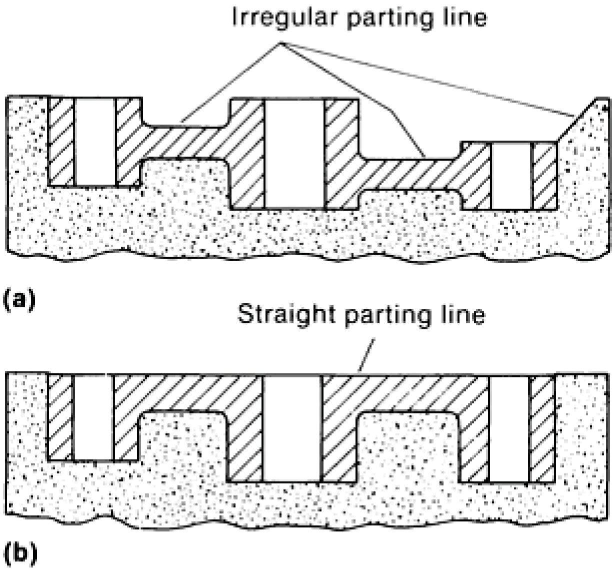


Fig. 28 Designing for a straight parting line to reduce pattern and casting costs. (a) Irregular parting line is a costly design. (b) Straight parting line is less expensive.

The factors that affect the resulting cost of castings and that have sufficient common traits to be independent of the casting process selected include:

- Requirements for surface finish and dimensional tolerances
- The number of castings to be produced
- The material selected for the casting
- The pattern material selected
- Any special or unusual testing/inspection or property requirements
- The casting design
- The casting process selected

Although casting costs are affected by these seven points, casting cost is only one element in the equation that determines the shipping dock cost of the final part headed to the consumer. If subsequent costs, for example, in machining, can be decreased by purchasing a more expensive casting, then the customer must weigh the potential cost savings against the cost of a less expensive casting.

The way in which consideration of casting and pattern costs alone can lead to false economies can be easily demonstrated by an example of the manufacture of a simple cube. The choice of parting line is usually not even considered by a casting customer, but is left to the quoting foundry. Because of this, many casting customers miss opportunities for innovative engineering solutions to shipping dock cost reduction.

For the cube example, there is a need to have the opposite sides of each face of the cube parallel and at right angles to one another. However, the need for draft angles on the tooling to allow removal of the pattern is in opposition to this. If this requirement is not conveyed to the casting supplier, he will undoubtedly quote the pattern equipment with a parting line as shown in Fig. 29(a). This parting line will be chosen by a casting supplier since it will produce the least costly pattern because it is the simplest pattern to make. Casting quotes are often rejected because of pattern prices; therefore, the casting supplier will generally opt for the lowest cost pattern.

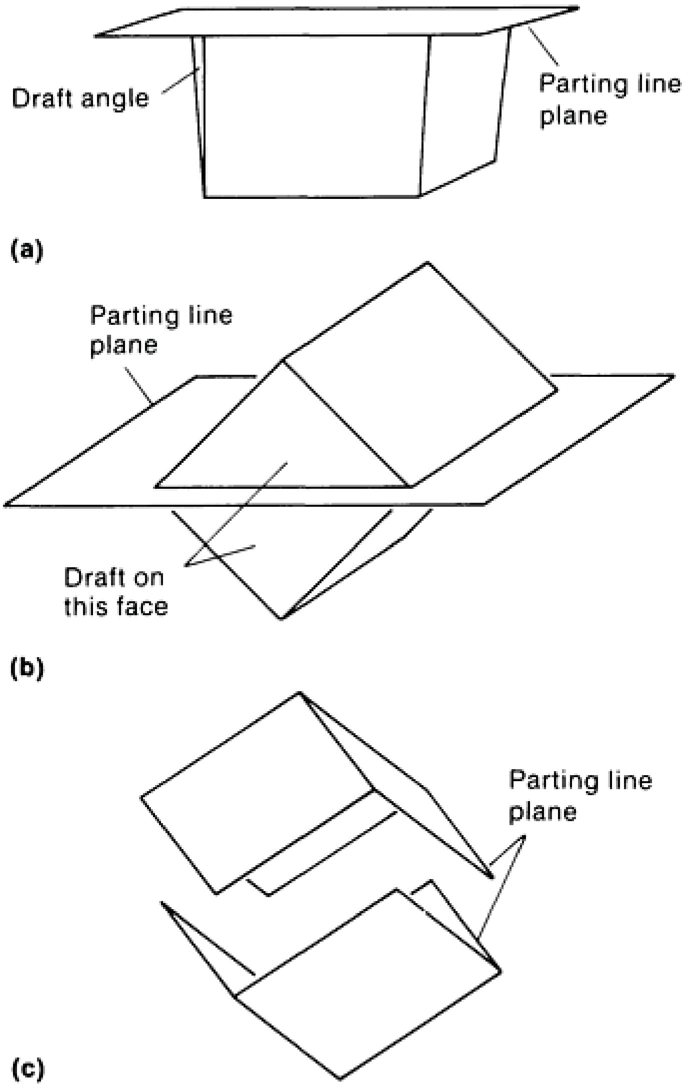


Fig. 29 Parting line options for a cube that must have as many sides as possible parallel and at 90° to each other. (a) Cube parted with four drafted sides is the least expensive option but does not meet design requirements. (b) Parting along the diagonal is a moderate-cost solution that results in four faces in compliance with design requirements. (c) Irregular parting is the most costly option, but is the only one that allows all sides to be parallel and at 90° to each other.

This choice of parting line will produce a cube in which only two of the opposing sides will be parallel to each other. A different parting that results in a slightly more expensive pattern is one in which the diagonal of two sides of the cube is used as the parting line (Fig. 29b). This would produce a part in which four of the opposing sides of the cube are parallel and at right angles to one another. However, the complicated parting line shown in Fig. 29(c) eliminates the need for draft on the tooling. Thus, all six sides of the cube can be made parallel to their opposing sides, and all of the sides will be at right angles to each other. This will be the most expensive pattern because of the complexity of the geometry involved. However, based on the requirement for parallel sides, it is the least costly method of producing the required shape.

The parting line should be considered in the design phase of a casting because of its importance in the final cost of the part. If it is not specified on the drawing, it should be requested to be returned with any casting quote; only in this way can the customer be assured of comparing equivalent manufacturing methods on the returned quotes. The customer should also request information on cores and other related production tooling in a quote. Only with this information can the best alternative be found for very low shipping dock cost. Without such information, the potential of various tooling designs cannot be determined, let alone used to develop a unique manufacturing approach to reduce the shipping dock cost. However, foundries usually consider such information to be proprietary.

If such manufacturing tooling design is of importance to the shipping dock cost of the final component, then it should be specified by the casting customer. This approach is virtually nonexistent in the industrial design of casting components, but it is essential if truly low cost component design is to be achieved.

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Dimensional Tolerances and Allowances

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Introduction

NO TWO MANUFACTURED PARTS are ever exactly alike, regardless of the process by which they are made. For example, castings made with supposedly identical processing in the same foundry will differ slightly from one another in terms of dimensions. This article will discuss the nature and causes of as-cast dimensional variations and the consequences of these variations in relation to tolerances.

Even more dramatic differences in dimensional reproducibility are seen when two casting sources manufacture the same casting. This is true even if both sources are using the same tooling to manufacture the shape, and it is a reflection of the total process capability of the source. The major variables contributing to the dimensional spread will be discussed in detail for each process method, and although they have some commonality among casting methods, the impact on the final shape can vary greatly, depending on the level of planning and process control exercised. It is acknowledged that the designer cannot exercise total control over the processing variables that cause dimensional variations, but an awareness of their existence and an understanding of their nature will assist him in specifying economically attainable tolerances.